Development of sensor based evaluation methodologies for developing world products

by

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ABSTRACT

Often consumers in the developed world have a wide range of options available to them when considering a certain product family, such as a smartphone. The plethora of options is in large part a result of the degree to which the supply chains have advanced in the developed world. Organizations such as Consumer Reports have distilled information about the products available to consumer in the form of comparative ratings charts to help them make a purchasing decision. These product evaluations provide valuable information on the quality of a product, but are limited to the perspective of the developed world consumer. In contrast, there are many barriers in providing a product to a consumer in the developing world. A multitude of poverty alleviating products have been developed, but few have been successful. The Comprehensive Initiative on Technology Evaluation at the Massachusetts Institute of Technology seeks to adapt product evaluation methodologies such as those employed by Consumer Reports to evaluate developing world products. This thesis documents the challenges in adapting the methodology and demonstrates that in order to create a successful product in the developing world, aspects of design, manufacturing, distribution, and consumer adoption must be assessed. A biomass fueled improved cookstove case study is presented to explain these four stages and how they may be evaluated. In addition, a sensor based method and neural network based processing algorithm is presented as a cost-effective and accurate way to gauge adoption of improved cookstoves.

Thesis Supervisor: Daniel D. Frey
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Chapter 1: INTRODUCTION

Quality and product evaluation have been explored from the perspective of economists and marketing professionals with a bias towards consumer preferences. This thesis seeks to provide an engineering perspective by linking the two concepts to the product development process and focusing on products fabricated for consumers in the developing world. This approach to quality and product evaluation is necessary because of the intricacies of the products, users, and markets in the developing world. Consumers in the developed world have access to a wide range of products and access to information so that they may make an informed purchasing decision. However, consumers in the developing world, particularly the poor may not have such avenues. It has been shown that product development has a direct influence on product success [1]. Therefore, in the resource constrained environment of the developing world the burden of providing a high quality product falls to the product developer.

The success of a product can be determined by using the following framework which is made up of four important stages: design, manufacturing, distribution, and adoption. From a product development standpoint, investments into evaluation of one or more of these phases can identify opportunities for iteration and improve the potential for market success of a product. Current product evaluation models focus on assessments of product quality with an emphasis on the stages of design and manufacturing, which may be a result of their consumer biased perspective. Although this information is useful to product developers, it is not sufficient to advance a product, especially in the context of the developing world. Due to a host of factors unique to developing world, distribution and product adoption are challenges that must be overcome for a product to succeed.

In this thesis, a description of quality is presented first to provide context for a discussion of different product evaluation models currently employed and challenges in adapting them to the developing world context. Then, a case study on improved cookstoves is presented to demonstrate the importance of distribution and adoption in a product's success. Finally, a field based instrumentation setup is described as a method to evaluate usage and performance of products. This is an emerging tool for product developers creating products for developing world consumers.

1.1 Successful Product Framework

The success of a product can be characterized in many ways. One common method is to monitor the market driven demand for a product. However, this method implies that purchase of the product leads to use of the product. This cannot always be assumed since certain products require sustained use in order to attain the intended benefits, which may necessitate a change in behavior. For example, purchase of a fitness tracking device does not lead to continued exercise or weight-loss. The device will record fitness patterns and may provide recommendations. But, acceptance of those recommendations is required on the part of the consumer for the device to provide the intended benefits of a more active lifestyle. The term "product success" is used here to designate a product that delivers its intended benefits from the perspective of the designer as well as provides desired utility from the perspective of the consumer. It is possible for a product to become obsolete over time due to technological advancement. But it is assumed that the time scale of adoption and sustained use is shorter than the time scale of technological advancement.

There are many anecdotes of superior products that did not gather momentum in the marketplace. For example, in 1993 Apple Computers released the Apple Newton. The Newton opened up the category of devices now known as Personal Digital Assistants (PDAs). The Newton featured a touchscreen with handwriting based input, which was not available in any other device. Despite the technologically innovative nature of the hardware it was discontinued around 1998. A successful product is the result of success in the stages of design, manufacturing, distribution, and consumer adoption. The Apple Newton was successful in terms of manufacturing and distribution as it was made and sold for approximately five years. However, the lack of consumer adoption, which is associated with aspects of its design led to its failure in the marketplace.

1.1.1 The Four Stages of Product Success

The four stages can be represented as a feedback loop with the desired product at the input and a successful product as the final output. Diagrams such as Figure 1 are common in product development references and depending on the goal of the diagram the steps can be delineated in various ways [2]. The format of a control system block diagram was chosen here to depict the iterative nature of the four key phases in the development of a product. These are the steps which must occur to transform an idea into a product that a consumer can use. Although Figure 1 presents the process in a linear fashion, iterations based on downstream feedback is a common source of non-linearity.

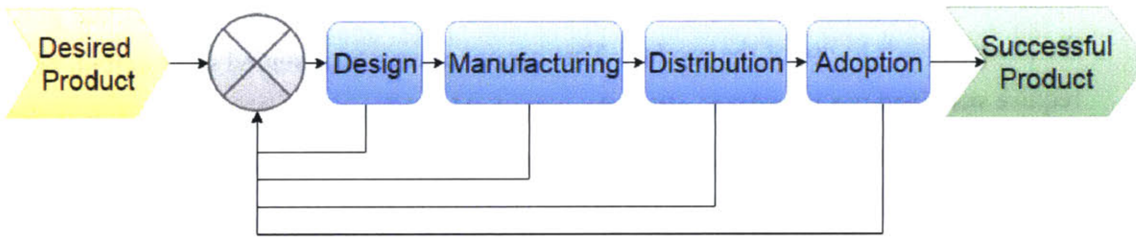

Figure 1: Product Development Framework

Furthermore, these stages do not occur independently and in many cases they have an influence on each other. A feedback path is drawn from each phase back to the beginning of the loop to indicate that downstream observations may result in changes for the remaining phases. For example, a manufacturer may deem a certain design infeasible due to cost or complexity, which would necessitate an iteration in design to facilitate manufacturing. A distributor such as a retail outlet usually prefers items to be stackable to reduce the shelf space required to display the item. Therefore, designers and manufacturers seek to optimize products for this distribution constraint. Innovations may occur in one or more of these stages to strengthen the success of a product and serve as a differentiator among competitor products. The feedback mechanisms are discussed in further detail in Chapter 3.

1.1.2 Importance of Distribution and Product Adoption

Current product evaluation models focus on the design and manufacturing aspects of a product with little to no mention of distribution and adoption characteristics. Although this is likely due to the consumer bias of these models, results of these evaluations can be used in some cases by the product developers to understand their position in the market and iterate on their designs. These models include attribute based evaluations and threshold evaluations. Attribute based evaluations measure a set of product features based on a predetermined set of criteria to generate a composite score intended to reflect the utility of a product. Threshold evaluations conducted by safety commissions and standards organization focus on certifying products past a given baseline. These models serve to inform a consumer or entity seeking to make a purchasing decision. Although design and manufacturing factors influence the distribution and adoption of the product, which are reflected in a consumer's purchasing decision, these evaluations do not explicitly mention them. This thesis focuses on using product evaluations for the creation of a successful high quality product by product developers not the selection of a high quality product by a consumer. As Garvin explains the interpretation of quality is different from the perspective of each stakeholder [3]. Therefore, since the results of distribution and adoption are particularly important to a product developer as it results in a products success or failure, these must be approached with different methods.

An illustrative example of the importance of distribution and adoption in developing world markets is with medicine. The World Health Organization (WHO) estimates that one third of the world lacks access to essential medicines. Frost et al. assert that "developing a safe and effective technology is necessary but not sufficient for ensuring access to technology and improved health." [4] This is a result of the fact that access is a complex composite of availability, affordability, and adoption. In addition, this issue is present in fields outside of health due to a complex series of steps that occur between technology innovation, diffusion, and appropriate use in developing countries [5]. On the other hand, companies such as Coca-Cola have seen great success due to their focus on distribution in the developing world [6].

Although the context of the developing world presents challenges in creating a successful product it also contains a plethora of opportunity. For example, labor costs are often low and may be conducive to keeping operating costs and product cost low while also reducing the demand for an international supply chain to distribute the product to intended consumers [7]. In other words, local manufacturing with low cost labor can result in ease of distribution.

1.2 Quality

The definition of a product presented by Maynes is adopted here as it represents the general consensus among researchers and professionals. A product is a composition of features from which a consumer derives utility [8]. Product evaluation is related to the concept of product quality since product evaluators make judgments about the quality of a product. Therefore, it is useful to develop an explanation of quality. Since this topic is a source of debate and lacks a precise definition, the various perspectives are presented to articulate the concept. First, it is important to note that generalization of product quality is difficult since the attributes of products differ widely as do the attributes used to measure quality [9].

Evaluations of a product are performed in many stages along the course of its development. The focus here is restricted to products that have already been released into the commercial marketplace. At this stage, evaluations are conducted by many stakeholders including: safety and standards organizations, third party consumer advocacy groups, consumers, competing organizations, and even the organization which released the product. Maynes, sets forth a simplistic definition of quality with a consumer biased perspective as, "the extent to which a specimen possesses the service characteristics [a consumer] desire[s]." [8].

Garvin argues that there are varying definitions of quality, which he proceeds to explain arise from four main disciplines: philosophy, economics, marketing, and operations management [3]. He claims each of these four disciplines draw from five basic approaches: transcendent, product-based, user-based, manufacturing-based, and value-based. First, the transcendent approach defines quality as a property that can be universally recognized, yet cannot be precisely defined. The second approach, product-based, defines quality as a measurable quantity originating from the products attributes. This definition allows for the ranking of products based on the amounts of each desirable attribute they possess. Third, the user-based approach defines quality from the perspective of a product's end user. Each user is assumed to have specific needs and preferences. The product that best meets the needs of each specific user will be regarded as the "highest quality" product by that user. The manufacturing-based approach is rooted in quality control. From this viewpoint, quality is defined as the conformance of the products attributes to its design specifications. Finally, the value-based approach combines two distinct ideas: performance and price. A "high quality" product is one that can provide the highest performance at the lowest price.

1.3 WHY MEASURE QUALITY?

Quality is important to a range of stakeholders. For example, for a company such as Toyota, quality is a point of differentiation and has provided a means of gaining market share in the automotive industry [10]. To a consumer, on the other hand, a product of poor quality may represent misspent money or a safety hazard.

1.3.1 Consumer Perspective

Maynes claims that measured quality has three uses [8]. First, it provides consumers a method of estimating their payoff. In other words, consumers can use quality assessments as a tool to maximize their payoff between searching for a suitable product and any gain they seek with the purchase of that product [8]. This is a necessary tool because professionals who create and sell products including designer, engineers, manufacturers and marketers, do so based on a set of functional requirements derived from a consumer need. However, each product developers may interpret and emphasize these requirements in various ways, resulting in products with slight differences in attributes and features. An illustrative example of this phenomenon is transportation. Many methods of transportation exist including cars, planes, and trains. Within the transportation subset of cars there are sedans, coupes, and sports utility vehicles (SUVs). Furthermore, there are many companies which manufacture sedans each of which have common and unique attributes, but still serve the purpose of transporting individuals from one location to another. The categorization and sub-categorization of transportation in this examples indicates the varied nature of individual user's requirements. A user must then decide which of these products best addresses their needs. A measurement and comparison of quality within such categories would allow consumers to understand the relative utility of each product. Maynes claims that the second benefit in measuring quality is that it represents the "informational effectiveness" of markets [8]. The efficiency frontier is a concept which represents the tradeoff between price and utility. A measure of quality provides insight into how well information about a product has percolated in the marketplace. Through a process of trial and error a majority of consumers will reach the same conclusions about quality, reaching the same efficiency frontier. This means that "high quality" products will have a high demonstrated demand in the marketplace. Finally, he notes the measurement of quality has an important place in economic theory in understanding the relationship of a product in a given market. Due to Maynes' consumer bias he does not mention the benefits of measuring quality for a product developer. It is important particularly in the international development sector as it guides developers on how to develop their products as well as how to get them into the hands of the users who will benefit from them.

1.3.2 Objective versus Subjective Quality

Quality has been shown to be an important factor in informing a purchasing decision [9], [11]–[14]. It is worth noting that from the perspective of a consumer, quality may be assessed through a variety of means including factors such as price, brand name, and advertising [9]. This behavior raises the important distinction between perceived quality and objective quality which is agreed upon by researchers. While objective quality is related to the technical performance of the specimen, subjective quality is an interpretation of quality [9]. Maynes makes the point that all interpretations of quality are subjective since the criteria of the quality is subjective [8]. But as Zeithaml notes, the use of objective quality is used to refer to a measurable quantity that is repeatable [9]. The framework of stages that contribute to the success of a product laid out in Section 1.1 refers to the fact that both perceived and objective quality are key factors of product success. Therefore, it is difficult to decouple them in judgments of quality. This issue is particularly apparent as methodologies to conduct the evaluation are explored in Chapter 3. It is apparent that assessments of objective quality can be made of design and manufacturing stages of a product because of the existing literature and existence of organizations such as Consumer Reports. However, quantifying perceived quality is also important because it provides user driven insights for improvements. Although this may not be a repeatedly measurable quantity in the way that lux of a light bulb is determined, it can be quantified. Some methods are discussed in Chapter 3 and a case study is provided in Chapters 5 and 6.

Chapter 2: PRODUCT EVALUATION MODELS

This chapter presents the methodologies employed by Consumer Reports (CR) and the Consumer Product Safety Commission (CPSC) to evaluate products in the developed world. Additionally, some research based evaluation methods for developing world products is also discussed. It is important to note that models employed by CR and CPSC are meant to educate and advocate for consumers, while this thesis seeks to develop a methodology to use evaluations to inform product developer. Application of these methods by a product developer can be challenging, but may still be of use in the development process. In addition, these models are the prominent examples of evaluations of commercially available products, therefore it is a relevant starting point.

2.1 HOW TO MEASURE QUALITY

Although neither Maynes nor Garvin provide insight into the methods to measure quality they offer the motivating thought that a product is a composition of multiple characteristics which can be measured. Maynes even provides a mathematical formula similar to a weighted average to quantify quality [8]. Maynes points out that quality assessments are dependent on knowledge, which is true both in terms of selecting the criteria to evaluate, as well as how those criteria are evaluated and their respective importance [8].

The measurement of quality is important, but it is not straightforward. Quality is not an inherent property of a product. Therefore, to measure quality proxy features or attributes are selected as an indication of quality. The selection of these parameters is important as it determines the method of measurement and the final learning point. Following Taguchi's philosophy on quality, important metrics will reflect physical quantities and should not be simplified into percentages. In other words, the physical parameters which influence the end function of the product should be measured not the resultant parameter. If a catapult has been designed to propel a ball ten meters, measurements of the total distance traveled should be logged not only whether the design specification was met. From these measurements the mean and variance of total distance travelled could be computed, which would provide an actionable piece of information reflective of the quality of the catapult.

2.2 CONSUMER REPORTS

As mentioned in Section 1.3 consumers use a variety of information to arrive at a purchasing decision. One of the sources of information is a comparative product evaluation such as one created by Consumer Reports. The model used by Consumer Reports to evaluate products falls under Garvin's definition of product-based quality. First, key product attributes that affect technical suitability relevant to users are determined. Then these attributes are scientifically measured with a rigorous testing protocol in multiple products within a family. Finally, the results are aggregated in the form of a comparative ratings chart with rankings assigned to each product of a given family.

2.2.1 Background

Consumers Union of United States, Inc. (Consumers Union or CU) is a 501 (c)(3) nonprofit organization best known for the magazine and website Consumer Reports (CR). The Consumers Union is referred to as Consumer Reports (CR) hereafter. Since Consumer Reports is a registered nonprofit organization it does not accept external advertisement. Instead, funding for its publications is raised through subscriptions. CR claims that this financial model allows them to remain impartial to businesses whose products they evaluate and enables them to have a continued impact in the marketplace. As of 2016, an annual magazine subscription costs $29.00 while a monthly web subscription costs $6.95. The Consumers Union 2015 Financial Statement indicates that $230,198,000 of its net $263,032,000 revenue came from "subscriptions, newsstand, and other sales" [15]. As of 2015, Consumer Reports' annual operating expenses totaled $204,786,000 while employing 591 people [15].

Consumer Reports has embraced the methodology of attribute-based product evaluation and has reduced to practice the ideas put forth by Maynes and others relating to product quality measurement. The stated goal of Consumer Reports is to transfer their institutional knowledge of a product to their consumers. The embodiment of their knowledge is communicated in the form of a comparative ratings chart published in the magazine and on their website.

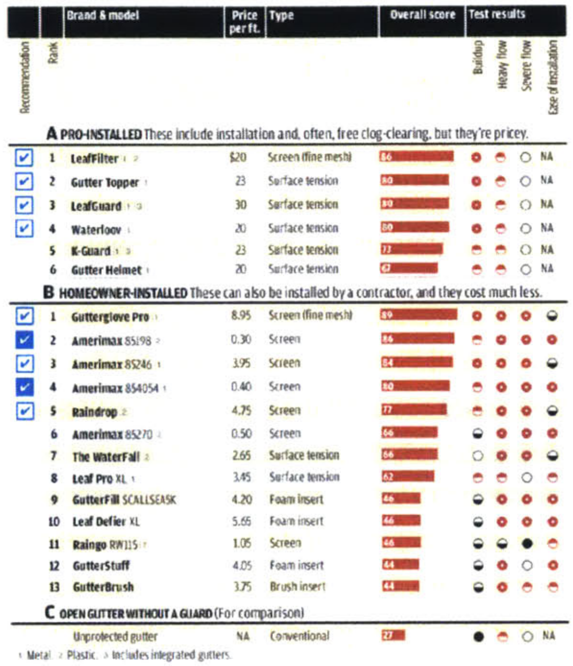

Figure 2: Example of Consumer Reports Ratings Chart for Gutter Guards

The consumer reports methodology of conducting product evaluations is maintained as a proprietary aspect of their business and has not been disclosed in public literature. As outlined in their mission statement, this may be a means of maintaining impartiality between manufacturers and preventing disputes regarding their testing protocols or weighting. CR claims that through an understanding of their evaluation methodology it is possible for a designer or manufacturer to tailor a product's functionality to perform in a superior manner but not provide the value consumers are seeking. This lack of transparency has not hindered consumer's subscription to their service.

2.2.2 Methodology

Consumer Reports use a range of tools in order to condense their institutional knowledge into the form of a comparative ratings chart. Hjorth-Anderson notes that CR evaluates only products that are functional, not those with only perceived quality traits such as furniture which is judged primarily on the basis of aesthetics [16]. Hjorth-Anderson describes the CR evaluation process in four steps: selection of commodity, selection of brands, definition and measurement of the characteristics, and finally the use of a set of unpublished weights to compute the overall quality [16].

The following framework further expands on the final two steps stated by Hjorth-Anderson: definition and measurement of characteristics and computation of overall quality. Specifically, the intermediate steps to construct a comparative ratings chart are described. This framework has been developed with the aid of available literature, collaboration with CR as well as general reasoning. This framework may be altered depending on unique concerns related to a specific product because generalizations about product quality are difficult to make as the function of each product is different.

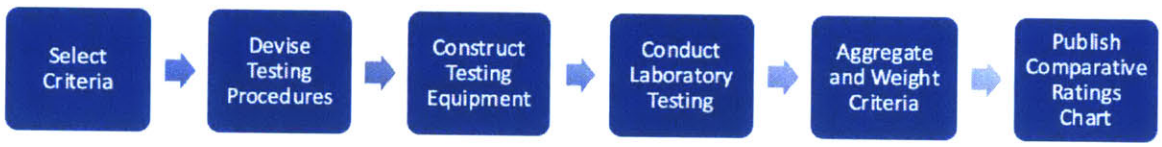

Figure 3: Consumer Reports Evaluation Framework

Criteria Selection

CR begins the process by conducting an initial consumer survey to determine which facets of a product in a given product family a consumer values. The results of this survey combined with expert independent opinion feed into the development of the criteria for evaluation. According to material listed on the CR website, these surveys consist of a millions of randomly selected users from their existing subscription population. The resources required to conduct and process the results of a survey at this scale are not negligible. In order to prevent the introduction of biases, such as response-bias, care must be taken in the manner that questions are posed so that objective and relevant information about user preference and satisfaction can be gathered.

The criteria accrued from the previous step would constitute the columns of the comparative ratings chart that CR releases in their magazine and website, as shown in Figure 2. For example, in a comparative ratings chart for cars one might see "ride comfort" and "braking distance" as criteria or columns. It is important to recognize that as the number of criteria and the number of products in consideration is increased, the cost of conducting the evaluation is also increased as more testing would be required.

Testing

After determining the important characteristics to test, CR would proceed to devise a series of tests and associated protocol to discriminate amongst the performance of different products with respect to these criteria. In order to carry out the specific tests often dedicated testing apparatuses must be constructed. For example, to test "ride comfort" of a car CR may take multiple cars and drive them over the same rough and smooth terrains with a series of accelerometers in the car and compare the data collected by the accelerometers. Since the tests are devised to emulate a combination of conditions ranging from common use to accelerated life these testing apparatuses cannot be purchased from an external vendor. In example, Consumers Union owns an Auto Test Track located in Colchester, CT. Such a facility is not only expensive to develop but also expensive to operate and maintain as it houses more than 20 staff members which include automotive engineers and technicians. According Consumers Union 2015 Financial Reports, the "Property and equipment" assets amounted to $57,607,000 which refers in large part to the testing facilities and equipment they have developed [15].

Weighting and Ranking Results

Using these testing rigs and the corresponding testing protocols, the performance of each product from a given family would be evaluated. Finally, using the survey data and expert opinion about the importance of certain product features they would create a corresponding weighting scheme for each criterion to combine the independent scores into an objective measure of the product's quality. "Content development", outlined in the steps above, accounts for $90,662,000 of the total operating budget[15]. The second largest expense in the operating budget is allocated to "Promotion and marketing", approximately $67,959,000 [15].

2.2.3 Criticisms

Criticisms of the CR methodology of product evaluation is centered on the selection of criteria and their relative importance. Although the criteria of evaluation are meant to represent an objective measurable aspect of quality, there is debate about how these are selected and if they are truly representative of the objective quality. Hjorth-Anderson a large skeptic of the methodology, does cede that it is a different matter to determine if the outputs CR produces are useful to consumers in making a purchasing decision [16].

The primary argument against the CR methodology is that the overall rankings are dependent entirely on the weightings assigned to each criteria. Although, criteria that make up objective quality may be measurable it is difficult to objectively combine them into a single value. Hjorth-Anderson argues that these weights are arbitrary and therefore the definition of overall measured quality is not useful for scientific purposes [16]. It is fair to extend this assertion to the broader category with the observation of Garvin's argument that quality is dependent on the stakeholder's perspective [17]. In the setting that Consumer Reports operates the determination of weightings seems to be developed through surveys. But it is important to recognize that there are biases involved in surveys. Furthermore, these quality rankings do not apply outside the context of a consumer. The combination of scores through weighting each individual criterion may be problematic. But, Consumer Reports provides the scores for each of the individual criteria and an individual consumer could make the choice of which features and attribute scores to trade-off while selecting the product which best suits their needs.

Another issue with ranking products in a given product family occurs when new products are introduced. For example, in the product family of automobiles, criteria such as miles-per-gallon (mpg), reliability and various aspects of the ride is tested. When gasoline powered automobiles are ranked against each other comparisons between mpg are adequate because they capture a limitation of the technology. However, when an electric car such as one produced by Tesla Motors is introduced into the market that consistency is lost. If CR attempts to use the mpg-equivalent for the electric car as a comparison it will outperform the competitors in that criteria. A more analogous measure for an electric car would be the maximum range per full charge since the battery capacity on electric cars is limited. CR has addressed this issue by producing evaluations with product families which are more narrow such as midsized car vs compact car. However, this increases the burden of the evaluation agency and does not address the question of whether a compact car is objectively better than a midsized car.

The financial resources associated with conducting product evaluations with the CR methodology are immense. Not only does CR employee a large number of people, their operating income and revenue are on the order of hundreds of millions of dollars. According to the disclosed financial statements, product testing amounted to $4,251,000 used to test approximately 2,000 individual products [15]. This means that approximately $2,000 is required to test a single product. However, because the resources such as testing equipment and staff time are not included in this calculation this is likely an underestimate.

2.3 Consumer Product Safety Commission

Another common model of product evaluation is employed by safety and standards organizations. These organizations seek to certify that a product passes a predetermined threshold of quality primarily in the interest of the consumer.

2.3.1 Background

The Consumer Product Safety Commission (CPSC) was formed by Congress in 1972 with the passing of the Consumer Protection Safety Act [18]. The role of the CPSC is to protect individuals from unreasonable risks of injuries or death associated with consumer products. As of 2008, the CPSC was reauthorized with provisions to increase its resources and capacity [19]. The formation of the CPSC came at a point of growing commerce within the United States. The CPSC maintains the relevance of its role due to the, "increased import volumes, the rise of Internet sales, and globalized supply chains" [20]. In 2008, over 35 million individuals required medical attention for injuries related to consumer products. Additionally, as of 2008, the value of U.S. imports under CPSC jurisdiction reached a high of $639 billion [20].

As of Fiscal Year 2015, CPSC employed 500 people with an operating budget of $123,000,000. A total of 246,486 products were tested using both internal infrastructure and third party laboratories. Over the past five years, 473 product recalls were issued annually resulting in 116 million total recalls of products from around the world [18].

2.3.2 Methodology

As outlined in the CPSC Annual report of 2013, five main avenues are pursued to fulfill their mission: Hazard Identification and Monitoring, Development of Safety Standards, Compliance and Enforcement, Public Outreach, and Intergovernmental Coordination [19]. The collection of information on injury and death statistics related to consumer products often forms the basis for the development of standards and need for product recalls.

A large part of CPSC's role is to develop and enforce standards. These standards fall into two categories: voluntary and mandatory standards. The CPSC asserts that it develops, "performance requirements, rather than design requirements, to give manufacturers the most flexibility". The voluntary standards are not strictly enforced by the CPSC since it does not have the jurisdiction to do so. However, since these standards are drafted by Standards Development Organizations

(SDOs) that are composed of industry, agency, and consumer representative's efforts are made to honor the agreements. Often the beginning of voluntary standards comes from the CPSC which has identified the need for such a standard based on information on injury and death. Mandatory standards, on the other hand, are federal requirements drafted by the CPSC in the case where compliance with voluntary standards has not eliminated the risk of injury or the adherence to a voluntary standard is unlikely.

Standards for both non-children's and children's products is outlined in the Code of Federal Regulations. Adherence to these standards is enforced through testing of the products. However, the requirements and guidelines for testing of non-children's products is minimal. Although, the CPSC has mandated that a "reasonable testing program" be developed and documented for each certified product actual testing may be conducted in-house or with a third-party test lab which can be shown with the issuance of a general certificate of conformance.

Children's products on the other hand must be tested by a third party CPSC certified lab demonstrated by the issuance of a Children's Product certificate (CPC). Additionally, periodic testing is required. The final distinction of children product versus a general use product is determined by the CPSC.

One of the negative results of this model is the increased cost to the consumer. Direct subscription costs are not paid to the CPSC, but the organization is funded in part by taxes. In addition, because companies must pay to have their products certified that cost is often bundled into the cost of product and passed on to the consumer.

2.4 Developing World Models

The developing world is different than the developed world in many ways such as culture and climate. Products fit for the developed world may not provide the same value to consumers in the developing world. Similarly, the adaptation of these product evaluation models for products aimed at developing world consumers is challenging. However, product quality is important to the poor. In the developing world, approximately 2.7 billion consumers live on less than $2 per day. Products of low quality that are either purchased or donated to these consumers may result in wasted capital or introduce a mistrust of technology. Product developers must strive to ensure high product quality to promote the livelihoods of those living in poverty. One method of doing so is by conducting evaluations of the four core criteria that influence a product's success: design, manufacturing, distribution, and adoption.

2.4.1 Randomized Control Trials

Randomized Control Trials (RCTs) are a common tool used in the field of medicine to gauge the effectiveness of a drug. The Abdul Latif Jameel Poverty Action Lab (J-PAL) has adapted this method for studies of international development programs and interventions. First a population is selected and divided into different treatment groups, in some cases one group may receive no treatment. In example, if a study aimed to determine the effectiveness of water purification on reducing incidences of diarrheal diseases in a specific village, the population may be divided into multiple groups. One group may receive a reverse-osmosis system, another group may receive chlorine tablets, and another group may receive cloth filters. By tracking key metrics such as number of reported cases of diarrheal diseases over a period of time, a comparison can be made about the effectiveness of each treatment. This methodology has produced concrete results that demonstrate the quality of various interventions and technologies in many cases throughout the world [21]. However, due to the scale required in these studies to reach statistical significance they are often expensive. Therefore, in some cases a RCT may not be appropriate or cost effective. Consequently, alternative methods should be pursued for monitoring the quality of international development projects.

2.4.2 CITE

The Comprehensive Initiative on Technology Evaluation (CITE) is a research group housed at the Massachusetts Institute of Technology (MIT) funded by the Higher Education Solutions Network (HESN) program launched by the United States Agency for International Development (USAID). CITE was established in 2013 with $5,000,000 in funding for five years by the USAID Global Development Laboratory (GDL). CITE is composed of an interdisciplinary team of faculty, researchers, and students from departments throughout MIT including: Department of Urban Studies and Planning and Department of Mechanical Engineering.

The goal of CITE is to conduct technology evaluations of developing world products and develop a rigorous methodology for the creation of these technology evaluations. CITE seeks to gain a fundamental understanding of a product's quality by using the "3S" methodology. This methodology involves evaluating a product from three interrelated standpoints: suitability, scalability, and sustainability. Suitability is concerned with the technical performance of a product and studying if a product performs its intended function. Scalability seeks to understand if a product can reach consumers by examining its supply chain. Sustainability involves studying the ways in which a product is used over time including reasons for initial purchase and factors that influence sustained use.

The purpose of conducting comparative product evaluation for the developing world is two-fold: allow NGO's and other procurement agencies or individuals to make informed decisions as to which products are properly suited for the consumers they are donating to as well as motivate manufacturers to develop better suited products for their end users.

CITE has produced an evaluation report on solar lanterns analyzing suitability, scalability and sustainability. The Suitability aspect of the report is focused on the technical performance of the solar lanterns and has adapted the Consumer Reports (CR) style of evaluation for products in the developing world. The discrepancies between the developing world and developed world have highlighted the need for targeted sustained product evaluation alongside innovation and development of infrastructure.

CITE - Attribute Based Methodology

The solar lantern suitability evaluation was conducted in a manner very similar to the CR style of evaluation. Various lanterns were chosen and tested in a laboratory setting to determine their comparative performance. The testing procedures were devised by consulting the International Electro Technical Commission (IEC) Technical Specification 62257-9-5 and expert opinion. The results were then consolidated into a comparative ratings chart and ranked according to performance. Additional details can be found in the CITE Solar Lantern Evaluation[1] and in the MIT Mechanical Engineering Masters Theses of Amit Gandhi[2] ("Development of methodologies for the testing and evaluation of solar lanterns") and Chris Pombrol[3] ("CITE Suitability : an exploration of product evaluation methodologies for developing world technologies").

product information				product attributes									features
make/model	overall score	cost (usd)	type (handheld/ desktop)	runtime on high setting		charge time		brightness	task lighting	ambient lighting	luminous range	water resistance	
				hours	score	hours	score	score					
SunKing Pro	88	$39.95	H/D	13.1	◑	8.7	●	●	●	●	○	◑	
WakaWaka Power	85	$79.99	H/D	21.2	●	17.7	○	●	●	●	○	○	
d.light S300	77	$49.95	H	6.1	○	13.3	◑	●	●	●	●	○	
SunKing Solo	67	$29.95	H/D	22.1	●	13.4	◑	◑	◔	◔	○	●	
WakaWaka Light	59	$39.99	H/D	18.1	◕	19.6	○	◔	◔	◕	○	●	
Firefly Mobile Lamp	58	$36.99	D	7.5	○	6.7	●	◕	◑	○	◔	●	
SunKing Eco	50	$19.95	H/D	19.1	●	8.2	●	○	○	○	○	●	
ASE Solar	50	$60.00	H	12.5	◑	19.0	○	◔	◑	●	◔	○	
d.light S2	43	$14.17	D	12.0	◔	13.7	◑	◔	○	◑	◔	◕	
d.light S20	42	$17.55	H/D	11.8	◔	9.8	◕	○	○	◔	○	●	
UniteToLight	29	$20.00	D	10.4	◔	17.9	○	○	○	○	◔	●	

Figure 4: CITE Solar Lantern Suitability Rating Chart [22]

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[1] http://cite.mit.edu/reports

[2] https://dspace.mit.edu/handle/1721.1/88387

[3] https://dspace.mit.edu/handle/1721.1/93739

Chapter 3: CHALLENGES OF DEVELOPING WORLD PRODUCT EVALUATION

The technology evaluations conducted by CITE examining solar lanterns and water filters has provided insight into the difficulties involved in evaluating products designed for users in the developing world. This chapter outlines some of those difficulties which stem from the direct adaptation of CR methodology by CITE. Since the CITE evaluation employs the "3S" methodology aspects of design, manufacturing, distribution and adoption were all considered. Although, the CR methodology maps well to the suitability aspects of the evaluation it is not as good a fit for the scalability and sustainability portions. Again it is important to acknowledge Garvin's position that product quality perceptions are dependent on the stakeholder. Since the perspective of each of the 3S's is different, the adaptation is limited. Furthermore, Maynes accepts that there is no uniform solution to the problem of product quality measurements [8]. In this case, developed world methodologies cannot easily be repurposed for the developing world due to the vast differences outlined in this chapter. The challenges in providing high quality solar lanterns to consumers in the developing world are significantly effected by the distribution and adoption mechanisms. This is why the focus must be shifted from the CR methodology which heavily emphasizes the design and manufacturing evaluation to assessments of distribution and adoption.

3.1 EVALUATION FRAMING

Prior to diving into the intricacies of conducting an evaluation, understanding the context for the evaluation is important. The key differences between the developed world and developing world, particularly in distribution and adoption of products calls for a targeted understanding of these traits as they serve as the critical barriers to the success of a product. Proper characterization of these stages will identify weakness and opportunities for improvement.

3.1.1 Market

The primary difference between CITE and CR is the characteristics of the markets in which these products are sold. CR evaluates products in the United States which has a stable and established market. The supply chains have been well developed and most products are ubiquitous. Any consumer in the United States can enter a store such as Walmart to purchase a television set in Boston, while another consumer can go to another Walmart located in San Francisco to purchase the same television set. Aside from taxes, both consumers would pay similar amounts of money for a product with identical features. One of the reason for the establishment of entities such as CR and CPSC is due to the vast array of products available to consumers through these well-established supply chains. However, this consistency is difficult to find in markets located in the developing world. Although products are beginning to penetrate these markets as well there are many other barriers to their success. This issue highlights the importance of understanding the distribution strategy of a product, since companies cannot always rely on large retail outlets to distribute their products.

Often the developing world is addressed as one large entity, however this simplification is not useful in the context of evaluating products. Each country referred to as a developing nation has a unique culture and geography in addition to other facets. These regional differences mean that often a single product is not effective in catering to the needs of every user in a given region. For example, treadle pumps are a technology useful to farmers with small plots of land with a readily available ground water source. However, a treadle pump may not be the appropriate technology for some farmers due to the lack of ground water or the size of land they wish to irrigate. Due to the unique needs of every region and the type of products available in those regions the method of evaluating products is not straightforward. Furthermore, the generalizability of the results is poor. The CITE evaluation of solar lanterns in Uganda contains some results that are due in part to the unique geographical and cultural context. It is questionable that all results deduced from the study can be applied to every country and region in Africa. This highlights the need for a targeted and deep understanding of adoption factors to promote the success of a product.

3.1.2 Audience

Organizations that conduct product evaluations in the developed world such as Consumer Reports and the CPSC, mentioned in Chapter 2, are successful in part because of their financial sustainability as an organization. Consumer Reports has cultivated a large base of subscribing users and CPSC has secured funding through government channels. In both cases the users of the results published by these organizations are the ones paying for it either through direct subscription or indirectly through taxes. It is important to recognize that both of these product evaluation models are meant as tools for consumers to make an informed purchasing decision.

In the developing world, users may not have the willingness or capacity to pay for services such as product evaluation. Therefore, as chapter 1 outlines, the demand for product evaluation lies with informing product developers or distributors rather than end users. If adequate resources are allocated to evaluating all four stages of the product development process presented in chapter 1 (design, manufacturing, distribution, and adoption) the needs of the end users will also be reflected in the final product.

3.1.3 Existing Indicators of Quality

There is an inclination among users to associate high price with high quality [16]. This is a trend present in both the developed and developing world. However, price-perceived quality studies have only examined a limited range of products and consumer types [23]. In the context of the developing world, this correlation between price and quality is also apparent with the examination of the CITE solar lantern suitability matrix [22].

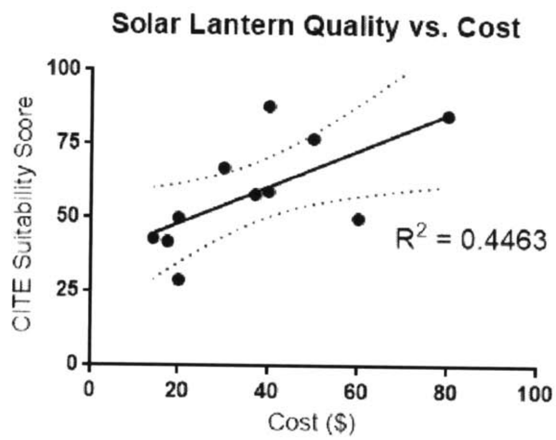

Figure 5: CITE Solar Lantern Quality-Cost Correlation

However, Figure 5 demonstrates that there are outliers. Both high-price low-quality and low-price high-quality products are present. Both of these types of products must be brought to the attention of consumers, which is one of the reasons for existence of organizations such as CR and CPSC. Since developing world consumers lack the financial capital to acquire information about high-price low-quality products it is important for product developers to properly address the needs of these consumers, and evaluation is a tool to gather an understanding of those needs.

3.2 Data Collection

A major challenge in conducting product evaluation for the developing world is in the collection of information. This collection of information is either done through experimentation or surveys. In both cases a large aspect of the challenge is dedicating monetary resources to support the collection of data. Additionally, there are opportunities for incorporating both methodologies into the evaluation of any of the four stages: design, manufacturing, distribution, and adoption.

3.2.1 Experimentation

Experimentation is the process by which knowledge about a product can be gathered. Experimentation in a laboratory or field setting is used in order to test relevant hypothesis about the quality of a given product and/or its family. Before conducting experiments, it is important to develop an experimental design to guide the experimentation process and organize data for analysis purposes. The development of an experimental design is useful in systematically evaluating objective quality. It is important to note that the creation of an experimental design is an iterative process.

3.2.2 Laboratory Testing

Typically, product testing done by organizations such as CR is conducted in a laboratory setting. Such an environment allows for careful control and targeted study of parameters. However, the setup of a laboratory for the purposes of testing requires investment in capital equipment. Laboratory-grade equipment offers high precision and accuracy at a high monetary cost. For example, a mass spectrometer, which is a machine used to characterize the chemical composition of a material will cost on the order of $100,000. In a university environment, machines such as these are not difficult to access. However, due to their high cost, they are infrequently purchased or upgraded. The lack of access to such machines makes it infeasible for a consumer to conduct such testing on their own. Furthermore, it is improbable that such an investment would be made by a development organization unless it is crucial in the development of their core technology.

Lab testing of products in the developing world is particularly difficult because of the lack of understanding of the product use behaviors and environmental conditions. One method of addressing this is to conduct a field visit to assess basic use cases and the environmental conditions. This data can then be used to recreate a representative test. However, investment in the construction of specialized testing equipment for these tests is still required. Furthermore, environmental conditions in the various parts of developing world can vary widely. For example, the average temperature and rain fall of southern India is vastly different than the average temperature and rainfall in northern Africa. This large variation increases the difficulty of creating a lab test representative of all of these conditions.

3.2.3 Survey and Observation

Some criteria although important to the objective quality of the product may not be explicitly testable which is where a survey can be useful. Surveys are a common tool employed by evaluators to acquire data. Although this data is subjective as it relies on written or oral solicitation of feedback it can reflect design and manufacturing characteristics. However, in the context of the developing world administering surveys for data collection presents many challenges. First, accessing users may be difficult as they may be located in remote regions. Furthermore, developing world users may not be accustomed to responding to surveys or interviews due to a lack of exposure. This introduces biases into the survey responses such as response or courtesy bias. Response bias refers to a set of traits in a user that lead to inaccurate or incomplete reporting [24]. The reasons for response bias include factors such as memory loss, phrasing of questions, or even demeanor of the researcher. Although these biases are also present in surveys conducted with users who are accustomed to surveys they may be more pronounced in this context. Biases can compromise the integrity of a survey and the gathered results. Since this is a critical pathway to iterate on design the inaccurate feedback to product developers may ultimately lead to failure of a product.

3.2.4 Field Work

Field work is a necessary part of understanding the context for the product under scrutiny. Since compensation for researcher time in addition to travel resources must be allotted to facilitate effective fieldwork, the cost of an evaluation can be immense and burdensome. This leads to a debate about how much resources to expend to gather data. In the developed world consumers are accustomed to and seek as much information as possible to make their decisions. However, this approach is often not possible in the developing world due to resource constraints.

Furthermore, as mentioned previously these users often lack capital to financially sustain an independent consumer evaluation group such as CR. Therefore, product evaluation should be conducted by a producer of a product, who can allocate the appropriate resources to evaluate features which may be detrimental to the success of their products. In this context those characteristics often reside in the distribution and adoption of their products.

3.2.5 Field Based Instrumentation

Low cost instrumentation embedded into products distributed to users in the developing world may help address the biases introduced from surveys. Additionally, remote reporting capabilities can be incorporated into these systems to provide real time data. This method not only provides complete data but also the opportunity for targeted improvements in distribution or adoption. It helps to provide the necessary feedback loop articulated in Figure 1 to promote the success of a product. The emergence of low cost sensors has enabled testing of products in the field setting.

Field testing is the process of conducting product testing in the context that the product is usually used. For example, CITE conducted field testing of solar lanterns in various towns in Uganda with product users. The primary advantage of field testing over lab testing is the access to real users and their behavioral use patterns related to a product. Lab tests that gauge durability and usability of a product attempt to emulate these conditions so that the product is tested in the same way that it is used. Incorporation of low cost sensors into products used by consumers can save time and cost associated with constructing a device meant to emulate those environmental and usage conditions. Furthermore, these sensors can also be used to assess the performance of products in the field. For example, by placing a flow rate sensor on a sample of five different models of water pumps the performance of them can be assessed similar to the methods used in a lab setting. The type of data that is gathered is dependent on the monetary investment in the sensors, which will dictate the degree to which the performance can be ranked. For example, a flow switch would provide information on whether a pump is in use while a flow rate sensor would provide information on the amount of water being pumped. The flow switch would cost less than the flow rate sensors but also provide less information. Therefore, it is important to acknowledge that the amount of information in this case is also dependent on the amount spent to gather the information.

Recent studies using field based instrumentation have shown promising results. Embedded instrumentation has helped to provide concrete data on the daily usage of technology such as cookstoves and water pumps [25]–[28]. Additionally, it has provided a means for implementing organizations which distribute products in the developing world to increase impact through targeted follow ups as well as report back data to their funders to increase access to funding.

Although embedded instrumentation has significant benefits in terms of tracking product usage and performance there are biases which can be introduced. It has been identified in the literature that use of sensors may influence the pattern of usage. A recent study by Thomas et al. used a cluster randomized trial to find that initial usage of a water filter was higher for households open to the presence of the sensor than those blinded to its presence. However, this difference declined to an insignificant level after four weeks. Additionally, no difference in usage was detected between cookstove users alerted to the presence of a sensor and not alerted [29]. The inclination of the users to change usage based on the presence of a sensor is likely dependent on their understanding of its function and the function of the product being measured. Due to communication barriers it is possible for users to believe that the sensor effects the performance of the device provided to them. In any case, it is important that more trials be conducted to understand the effects on usage and perception of the user based on the presence or lack of a sensor.

Chapter 4: IMPROVED COOKSTOVES CASE STUDY

In this case study, relevant literature is used to describe and informally evaluate aspects of design, manufacturing, distribution, and adoption of an improved charcoal cookstoves. Two specific stoves are used in this case study to compare and contrast these four aspects from the perspective of a product developer. This comparison is useful as it demonstrates that differences and similarities in the approach to these four aspects may yield different results. Additionally, it highlights the benefits of conducting evaluations of these four aspects and how they may be used for further iteration and refinement of a product to promote its success.

As noted by many scholars the distribution and adoption of these cookstoves has been slow despite the drive by large organizations such as the Global Alliance for Clean Cookstoves (GACC) [30], [31]. A comprehensive literature review of cookstove technology published in 2015 by Sutar et al. demonstrates that literature is largely focused on design and technical evaluation of cookstoves [32]. In addition, the review demonstrates that fewer studies focus on the manufacturing, distribution, and adoption of cookstoves. In order to realize the benefits of improved cookstoves on a large scale, it is important to characterize these factors in addition to the technical factors.

4.1 BACKGROUND

4.1.1 Terminology

Terminology for this discussion is adopted and modified from "Cleaner Hearth, Better Homes" by Barnes, Kumar, and Openshaw [33].

1. Traditional stove: either open-fire stoves or cookstoves constructed by artisans or household members that are not energy efficient and have poor combustion features [33].
2. Improved cookstove: cookstoves developed based on higher levels of technical research; these cookstoves are generally more expensive and are based on higher standards that include safety, efficiency, emissions, and durability; among others, they might include wood, charcoal, pellet, and gasifier cookstoves [33].
3. Biomass fuels: include wood, charcoal, agricultural waste or other organic fuels [30].

4.1.2 Benefits of Improved Cookstoves

Improved cookstoves present benefits both inside and outside the household. Benefits in the household include: saved time, saved money, and reduced household air pollution [34]. Benefits external to the household include: reduced pressure on local energy resources and reduced greenhouse gas emissions [34]. These benefits are a result of improved heat and combustion efficiency over traditional cookstoves. The energy efficiency of improved cookstoves saves money and time because households do not have to purchase or collect as much fuel, in addition to reduced time for cooking meals. These in turn reduces both greenhouse gas emissions as well as pressure on the local energy resources such as forests. With sustained use of an improved cookstove, the lifetimes savings can be significant. A study conducted in Niger shows that the typical annual savings for a family amount to 335 kg of wood or $15 per year, in a region where the average annual household income is between $300 and $370. This data was estimated through lab testing and then verified through interviews [34].

4.1.3 Indoor Air Pollution

About half of the global population relies on solid fuels, such as biomass and coal, for basic energy needs [31], [35]. According to the World Health Organization approximately 4.3 million people die annually, due to illness developed as a result of household air pollution [35]. Many households using solid biomass fuels burn them in open fires or traditional cookstoves with poor combustion characteristics and low thermal efficiency. As a result, high levels of particulate matter, carbon monoxide, and other pollutants are emitted [36]. The use of these fuels is also a notable source of air pollution, deforestation, and global climate change [37], [38].

Dissemination of improved cookstoves and cooking fuels is a key intervention to combat this issue. Improved fuels and stoves offer a cleaner and more efficient alternative to current practices [39]. The Global Alliance for Clean Cookstoves (GACC), founded in 2010, has stated the goal of converting 100 million households to clean and efficient stoves and fuels by 2020[4].

Although this case study focuses on improved biomass cookstoves it is not the only improved cookstove that available and is by no means the only option to combat the issue of indoor air pollution. Significant research and policy efforts have been dedicated to this topic and therefore

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[4] GACC Website: http://cleancookstoves.org/

is well positioned to address this problem. Since a large fraction of the world's population relies on solid fuels it is a practical avenue that is a stop gap measure as users continue to climb the energy ladder to modern fuels that are less polluting as affluence grows [40]. But the growth in population and projections from WHO indicate that into the next 50 years solid fuels will remain a large part of addressing energy needs [35].

4.2 Design

Improved cookstoves can be operated using a variety of modes including: electricity, solar, or biomass. This case study focuses on biomass fueled cookstoves which present risks of deforestation and household air pollution. The Global Alliance for Clean Cookstoves (GACC) has assembled a catalog to document a range of improved cookstoves and their performance[5]. These cookstoves are categorized based on a variety of factors such as style, fuel type, emission rating, etc.

4.2.1 Three Stone Fires to Improved Cookstoves

In open fires, a common method of cooking, only 10 to 40% of heat is transferred to the pot [41]. Open fires are also commonly referred to as three stone fires due to the arrangement of the pot on top of three stones above the open fire. Improved cookstoves seek to improve combustion efficiency and improve heat transfer efficiency to maximize the energy transfer from the fuel to the pot. All improved cookstove designs include an enclosed combustion chamber and method of holding a pot. The type of fuel used for cooking can effect design factors such as the size of the combustion chamber. For example, for wood burning stoves a chimney is often recommended as a means of removing soot and smoke produced during the combustion process. For the purposes of illustration, we will focus here on charcoal stoves, which have many common characteristics found among other improved cookstoves.

Cookstove designs have evolved throughout much of human history. Objectives to reduce fuel and energy usage along with emissions has spurred more research interest in the past few decades. In recent years the accessibility of computing power has given rise to the use of CFD and other comprehensive mathematical models to understand and optimize cookstove designs.

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[5] GACC Stove Catalog: catalog.cleancookstoves.org/stoves

Additionally, lab and field testing methodologies have been devised for validation of designs [32].

4.2.2 Test Methods

In order to assess the performance of a cookstove, experimentation is required. Two of the primary indicators of performance are the combustion and thermal efficiency of the stove. Standard protocols for both laboratory and field testing have been developed by many organizations. Lab testing allows for distinction among stoves, while field testing is a more accurate indication of actual performance. Field testing is a necessary complement to lab testing because environmental variations such as temperature, humidity, and user interaction are introduced. Furthermore, recent studies have shown discrepancy between field and lab testing since the combustion of biomass is a complex process which is sensitive to factors such as fuel variations and local cooking preferences which are generally present in the field [34], [38]. Although many standards and methodologies have been developed for both lab and field testing, debate among academics, industry-experts, and regulatory authorities has resulted in low adoption of comparable test procedures [42].

Some of the common protocols for stove performance characterization are: Water Boiling Test (WBT), Heterogeneous Testing Protocol (HTP), Controlled Cooking Test (CCT), Kitchen Performance Test (KPT), and Uncontrolled Field Test (UFT) [43]. The GACC has curated the protocols on their website[6] and Berkeley Air Monitoring Group's "Stove Performance Inventory Report" provides a brief comparison of common methods [43]. It is important to note that a specific protocol may not be suited for all stove types. The WBT is the primary test used for the assessment of stove performance as it provides two important metrics: thermal efficiency and indication of emissions (grams pollutant per MJ-delivered). However, there are many variations of the WBT have been proposed such as WBT 4.2.3, WBT 3.0, Chinese WBT, and Indian WBT.

In an effort to provide formal standards the cookstove sector has approved a set of performance indicators under the ISO International Workshop Agreement (IWA)[7]. The IWA standards categorize stoves into Tiers between 0 and 4, with 4 being the best. These tiers are

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[6] http://cleancookstoves.org/technology-and-fuels/testing/protocols.html

[7] http://www.pciaonline.org/files/ISO-IWA-Cookstoves.pdf

currently calculated from emissions and fuel use related to outputs of the WBT 4.1.2. The IWA also recognizes the need for performance tiers related to facets such as durability and intends to include them as protocols are developed and become available publicly.

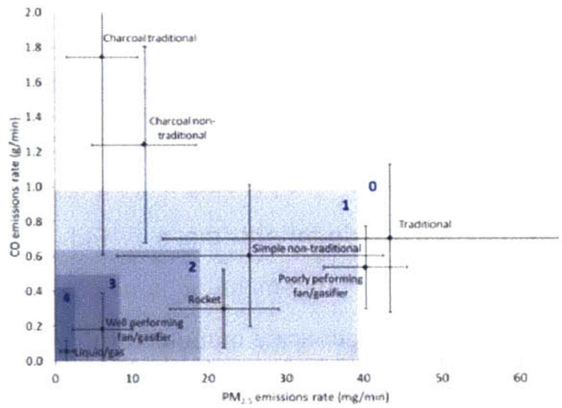

Figure 6: WBT-based Tier Rankings of Stoves (x-axis: Particulate Matter Emissions; y-axis: Carbon Monoxide Emissions)

Figure 6 above shows the current standards with respect to particulate matter and carbon monoxide emissions for tier ranking of improved cookstoves [43]. The industry has invested heavily into the testing and standardization of test procedures in support of increasing the performance of stoves. Although the technical performance of these stoves as outlined in the IWA tiers is important, it alone is not capable of addressing the issue of indoor air pollution.

4.3 Manufacturing

Manufacturing cookstoves is a key step in attaining the GACC goal of converting users to improved cookstoves. The designs developed and tested with the methods outlined in the previous section must be produced by a manufacturer before a consumer can purchase or use the stove. This section outlines some of the methods and considerations involved in the manufacturing of cookstoves. This section is composed of information gathered from field observation and informal conversations with relevant stakeholders. Aside from do-it-yourself (DIY) stoves, which are common in the developing world, biomass cookstoves can be classified into two categories based on the scale of their production: low-volume and high-volume. DIY stoves are not considered manufactured products as they are usually custom made for an individual household and is not included in this discussion. Furthermore, DIY stoves are difficult to characterize with the IWA tiers because there is no standardization. Those which have been tested tend to fall into the tier 0 category, which is outside the intended range for an improved cookstove. Manufactured stoves, on the other hand, typically have a common design which is produced at scale.

The high level advantages and disadvantages of the two manufacturing approaches is presented in this section. There is no evidence to suggest that one approach is more effective than the other. Furthermore, the high-volume production of stoves is not the clear and obvious approach. In fact, this examination also highlights that a hybrid of these two models may also yield success. In other words, if high-volume manufacturers move operations to local contexts or low-volume manufacturers invest in larger scale manufacturing operations more market success may be garnered.

4.3.1 Improved Biomass Cookstoves

The AEST Makaa stove is used as the representative low-volume stove and the EcoZoom Jet is used as the representative high-volume stove. The Makaa Stove is a tier 2 stove and the Jet is tier 3 stove. Both of these stoves are primarily intended for use with charcoal fuel. However, their design characteristics are similar to those used with other biomass fuels with slight variations in some dimensions such as height of combustion chamber.

Figure 7: (left) AEST Uganda Makaa Charcoal Stove; (right) EcoZoom Jet Charcoal Stove

4.3.2 Low-Volume Manufacturing

Low-volume manufacturers typically produce in the range of 10's to 1000's of cookstoves per month. These cookstoves are normally produced in a local or regional context, such as the Makaa Stove in Soroti, Uganda. Due to the lack of access to capital infrastructure in the local context, low-volumes of production often use labor intensive manufacturing processes. Most of these low-volume stoves are produced by skilled artisans with locally sourced materials. For example, the external components of the AEST Makaa stove such as the casing, pot supports and handles are made of sheet metal. An artisan uses a leaf-spring and some type of anvil to hammer and form the sheet metal.

Figure 8: Artisan constructing a Makaa Stove

Low-volume manufacturers are often restricted to locally available materials. Typically, these manufacturers use a clay fired liner as the combustion chamber while concrete is used as the primary mass which holds the clay liner and outer casing in place. The hand-made nature of these stoves often results in a limited product life and significant variations, which may affect the performance of the stove. Despite being constructed by hand the price of a low-volume stoves is often lower than their high-volume counterparts. Presence in the local context allows these manufacturers to easily understand and adapt their designs to the local cooking preferences of their users. Additionally, they benefit from locally available channels of distribution such as an open air market or word of mouth. In the developing world this is a significant advantage as large amounts of capital are required to set up distribution channels to provide access to products. Further growth in a local manufacturers business might allow for development and investment of local capital as well as the potential of sourcing more exotic materials for production of the stoves.

4.3.3 High-Volume Manufacturing

High-volume manufacturing of stoves is typically done internationally in places such as China or India where industrial factories exist for other products and can be adapted for the production of stoves. Although India and China are large markets for improved cookstoves, the distribution mechanisms for high-volume manufacturers is usually different than their low-volume counter parts. In other words, a user cannot approach the factory and purchase a stove, they would have to seek out a licensed distributor or retail outlet. A low-volume manufacture relies on local markets while a higher volume manufacturer seeks to export its products. However, recently the stove manufacturer, Burn, has established a manufacturing site in Nairobi, Kenya. This is one of the first instances of a local mass manufacturer. This may be an emerging model to facilitate ease of distribution and increase local employment. Conversely, it is improbable for a low-volume manufacturer to produce stoves and export them to other markets because of the costs associated with such an operation.

As in the case of most products, high-volume manufacturers are able to exploit economies of scale to reduce cost. This is particularly important as they are able to source more expensive specialized materials and use manufacturing techniques that are infeasible on a small scale. The use of specialized materials and tooling often results in a longer product life and overall higher performance which can be amortized into the cost of each stove. For example, the stovetop of the EcoZoom Jet stove is made of cast iron which is durable and resilient to high temperatures. The case of the stove is constructed from sheet metal but unlike most low-volume stoves it is deep drawn from a single piece of sheet metal. Deep drawing requires the use of hydraulically driven capital equipment. Additionally, in place of concrete the Jet uses a proprietary insulation material with a high thermal resistivity. Due to the fact that these stoves are produced in a factory setting they benefit from large scale quality control practices that ensure minimal variations in dimensions that may influence the performance of the stoves. This build quality also results in a higher perceived value which is often an important factor in the adoption of cookstove products. However, unlike low-volume manufacturers, high-volume producers suffer from a lack of flexibility. Product variants, such as the EcoZoom Plancha are often introduced to address local cooking preferences. However, this requires significant capital investments due to tooling and materials.

4.4 Distribution

This section focuses on the methods of cookstove distribution. Distribution of improved cookstoves is a significant challenge with varying degrees of success thus far. Various methods exist to distribute these stoves including large scale dissemination through international relief agencies as well as local market based approaches. Distribution is the step immediately following the design and manufacturing of the stove. Therefore, a critical link between the two stages exists and the distribution modes can be examined from the perspective of the two primary types of stove manufacturers: low-volume and high-volume manufacturers. These manufacturers broadly follow two distribution mechanisms: market-based and subsidy-based. Pure market-based or pure subsidy-based distribution strategies has seen limited or short-lived success [33]. Often these distribution mechanisms are not independent, many interventions have begun with large subsidies and transitioned to a market based approach. In some cases, market based approaches will take advantage of subsidies to facilitate development and growth towards sustainability. Therefore, it is difficult to separate these approaches. This section presents the evolution of these distribution strategies which highlights the fact that there is no single method of distribution that has or will be successful.

4.4.1 History of Cookstove Distribution

Early stove programs in the 1970s and 80s began with large scale institutions such as governments, international donor agencies, and NGO's. They operated with significant subsidies to make stoves accessible to all users under the assumption that the benefits of cookstoves were obvious. However, discounting the importance of the user centered factors such as local cooking preferences the success of these programs was limited. Subsequently, programs shifted focus to commercial approaches which has seen success in a few contexts including China, Kenya (Jiko), and Guatemala (Lorena) due in part to the targeted regions and operational strategies [33].

4.4.2 Distribution by Low-Volume Manufacturers

Low-volume manufacturers and high-volume manufacturers both have unique advantages and disadvantages in terms of distribution. Low-volume manufacturers are able to leverage local markets because of their manufacturing location. This enables them to cultivate a user base that does not require the need for extensive promotional campaigns or large and intricate distribution networks. In addition, they can offer financing programs and collect money with limited default rates, which can be challenging to implement for larger non-local organizations. However, market based approaches have a hard time reaching the poor customers who are often the most in need of these stoves. This is because the economic viable price for the cookstove business may be higher than the economic resources available to these low income users.

4.4.3 Distribution by High-Volume Manufacturers

High-volume manufacturers on the other hand have a challenge in penetrating the market. Due to the large capital investments in manufacturing they rely on distributing cookstoves in large volumes to remain financially sustainable. Therefore, they are often supported by other large entities such as international aid organizations, governments, or NGOs either in the form of grants or purchase orders. This support may also take on the form of subsidies to reduce the costs of the stoves to the end users or a distribution network. It is noted by Barnes et al. that most successful programs have had a dedicated implementation group [33]. This allows these manufacturers to focus on production while better suited stakeholders disseminate the stoves. This top-down approach is often effective in providing many users with well tested stoves. But due to the heavy reliance on the implementing partners and governments they are difficult to transition to a sustainable business. This is in part because the government subsidies may be cut back since the goal of the subsidies is to spur the marketplace and connect users with effective products. However, this does not mean that these products cannot be successful with government subsidies. With effective local market penetration instigated by the subsidies these manufacturers can develop the distribution networks required to sustain and grow their business. These is essential because the cookstoves that these programs disseminate have a limited lifetime and must be repaired or replaced.

4.5 Adoption

Improved cookstoves dissemination began in the 1970s. Many programs have been implemented throughout the world that aim to provide people with technologies that would improve their livelihood. These programs ranged from small scale distribution through NGOs up to nationwide initiatives such as those in Nepal, China, and Mexico. Early programs assumed that the benefits of these improved stoves such as reduced fuel use and decreased cooking time would be apparent to users. However, a host of socioeconomic reasons as well as institutional difficulties with monitoring and evaluation of stove programs has resulted in lower rates of adoption and sustained use than expected [40]. Manibog states that as of 1984 fewer than 100,000 stoves were distributed worldwide, but 10-20% fell into disuse and 20-30 % were used intermittently.

4.5.1 Factors of Cookstove Adoption

Many studies have been conducted in a wide range of contexts to understand the factors that affect the adoption of improved cookstoves. Studies often use socioeconomic background of the users and data about daily usage gathered through surveys or sensors and correlate them to identify trends and key factors. The studies have revealed there are many important factors, which Puzzolo et al. summarizes into seven domains [44]:

1. Fuel and technology characteristics
2. Household and setting characteristics
3. Knowledge and perceptions
4. Financial, tax and subsidy mechanisms
5. Regulation, legislation and standards
6. Market development
7. Programmatic and policy mechanisms

The level of abstraction in these domains indicates the degree of complexity in understanding the key factors associated with desirable adoption rates of improvied cookstoves. In the particular case of improved biomass cookstoves Puzzolo et al. cites that based on a longitudinal observation of 57 adoption studies some of the critical factors include [44]:

- Meeting users' needs, particularly for cooking main dishes and being able to use large enough pots;
- Providing valued savings on fuel;
- Offering products of a quality that meet user expectations and ensure durability;
- Having success with early adopters, in particular opinion formers;
- Guaranteeing support (e.g. loans) for businesses producing and promoting ICS;
- Ensuring support to users in initial use, and for maintenance, repair and replacement;

- Developing an efficient and reliable network of suppliers/retailers;
- Providing financial assistance for equitable access and/or for more expensive ICS.

4.5.2 Complexity of Promoting Adoption

A key conclusion identified by Puzzolo et al. is that some factors are critical for success, but none guarantee it. Furthermore, addressing critical factors is often not straightforward as they may occur at many levels such as the household level or national level. In many cases the methods used in dissemination of the stoves may not recognize the importance of certain critical factors as they can vary based on the social, cultural, or regional contexts. Puzzolo et al. recommends careful planning through an in-depth understanding of the local context as a critical step for programs to take in order to maximize adoption rates. In addition, adequate monitoring and evaluation infrastructure should be laid out in order to assess the longer term sustained use of stoves.

Despite a growing understand of the factors which influence adoption the problem still remains. Furthermore, the methods used to monitor and evaluate the adoption of stove dissemination programs has evolved over time. Early studies used intermittent surveys to gather data about the adoption and sustained use of stove programs. But as mentioned in Chapter 3 Section 2.2, studies have revealed that surveys can introduce various biases that provide misleading results. Emerging methods of monitoring and evaluation involve the incorporation of sensor technology in the field, which is further discussed in the next chapter.

Chapter 5: Data Logging System and Analysis Methods For Assessing Cookstove Adoption

With the decreasing costs and the increasing availability of electronic components along with the open source movement, instrumentation is growing cheaper and more accurate. For example, a 3-axis accelerometer costs approximately $1[8]. Such a device would be fit for a wide range of use cases that require motion detection to capture usage patterns. Connecting an accelerometer to a microcontroller such as the Atmega328, found on the ubiquitous Arduino Uno, and including a data storage medium, such as an SD card, can increase the capabilities of a field testing device. This chapter describes the design and development of an instrumentations system and processing algorithms to study the adoption of improved cookstoves.

5.1 Stove Use Monitors

Among other benefits such as fuel savings, the use of improved cookstoves has been shown to have an effect on indoor air quality (IAQ) including metrics such as suspended particles (PM2.5) and Carbon Monoxide (CO) [30]–[32], [38], [45]. It is important to recognize that benefits of improved cookstoves are realizable only if users adopt and continue to use these stoves [25], [26]. Stove use monitors (SUMs), comprised of a temperature sensor and some means of data storage, are one method of monitoring use of a cookstove.

5.2 Sensor Construction

Maxim IC's iButton sensors have been used in prior studies as SUMs [25], [26], [46]. These sensors are sold at a cost of approximately $40 per piece (or $20 per piece when purchased in quantities of one thousand) with a storage capacity of 2048 data points (a more expensive version capable of 8196 data points also exists)[9]. At a continuous ten-minute data logging rate,

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[8] Digikey: http://www.digikey.com/product-detail/en/stmicroelectronics/LIS2HH12TR/497-15069-1-ND/5043075

[9] Maxim: https://para.maximintegrated.com/search.mvp?fam=data-loggers&808=iButton&1028=Temperature

2048 data points will correspond to approximately 336 hours or two weeks of data storage capacity (8196 data points would translate to 56 days or 1344 hours). Although these sensors have a small footprint, the limited data capacity increases the burden on the researchers and participants as it requires frequent visits to participant homes to collect data. This is has been noted as an important constraint as frequent visitation is expensive and often leads to drop out of study participants [25].

To decrease the burden on researchers and participants, a new SUM (Sensen SUM) was designed with increased data storage capacity. The Sensen SUM, uses an RFduino microcontroller with an internal temperature sensor and a 2000 milli-amp hour (mAH) Li-Ion battery (See Appendix A for Printed Circuit Board Schematic and Board Layout). The SUM also includes an on-board accelerometer and micro-SD card holder, which were not enabled for this study. The increase in data capacity and battery life allowed for a faster sampling rate of every five minutes, thus increasing the resolution of the data. It was estimated that this setup would allow for approximately six months of continuous data logging with the limiting component being the battery life.

Silicone was applied to unit increase water resistance. However, it should be noted that silicone can be corrosive to electronics and was not a wise deign decision. All of the components were packaged into a small tin and riveted to a small section of rectangular steel tube. The steel tube was included as a mechanism to dampen the heat transfer from the cookstove to the Sensen SUM to address concerns related to overloading the temperature sensor and damaging the Li-Ion battery. The steel tube also provided a method to attach the SUM to the cookstoves. Physical attachment of the SUM to the stove is an important feature because anecdotal evidence has suggested that users may move their cookstoves on a day-to-day basis or during cooking events.

Figure 9: Internal Components of Sensen SUM

5.3 Sensor Deployment and Data Collection

A stove adoption study using SUMs was conducted in conjunction with Appropriate Energy Savings Technologies Limited (AEST- Soroti, Uganda) which is the manufacturer of the stove considered in this study – the Makaa stove. Further details of the study are proided in chapter 6.

Thirty Sensen SUMs were deployed at households in Soroti, Uganda for a duration of approximately 150 days. Twenty SUMs were deployed on stoves belonging to new users, who had just purchased the stove in at least 6 months prior to the start of the study. The remaining ten SUMs were deployed on stoves belonging to existing users, who had purchased the stove at least one year prior to the start of the study. Due to sensor malfunction 9 sensors recorded partial data over the course of the deployment. The remaining 21 sensors (13 new users, 8 existing users) captured 945,000 data points totaling 3,150 days or 75,600 hours of active measurement.

Figure 10: Examples of Sensen SUMs attached to AEST Makaa stoves

5.4 SUM Data Processing

The use of SUMS for understanding adoption and sustained use of improved cookstoves is a growing sector of research. Therefore, standardized methods of data processing do not exist. Researchers studying adoption of cookstoves have devised algorithms based on prior literature. However, Pillarisetti et al. and Ruiz-Mercado et al. have articulated that a standardized method would allow for better comparison of research outcomes related to adoption [25], [26], [46]. Here a SUM processing algorithm is presented with accessible code in an attempt to begin standardization.

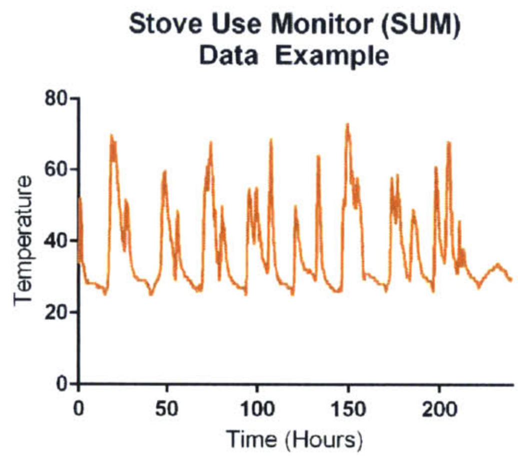

Figure 11: Example of SUM data

5.4.1 Existing Methods

Figure 11 shows typical data captured from a SUM over a 10 day period. Inconsistencies in the height and spacing the temperature makes it difficult to identify stove use events and determine the duration of those events. In some cases, multiple peaks can be associated with the same cooking event and may have been caused by stirring or addition of fuel. Pillarisetti et al. use a threshold value and a set of cases to distinguish stove use events and their duration [26]. The threshold is a function of the average and standard deviation of the ambient temperature of the region. Another important constraint added is that threshold crossing points (above threshold to below threshold or vice-versa) must be separated by a minimum of 40 minutes to be classified separate events. This method of data processing places a burden on the researcher to anticipate all possible instances that should be classified as a stove use event.

Another method of processing SUM data used by Ruiz-Mercado et al. [46] involves peak detection, peak filtering, and clustering. First, all peaks are identified and filtered. Peaks below a certain threshold such as those relating to ambient temperature variation are classified as non-events. Then, a windowing algorithm is used to cluster peaks into three bins relating to a three-day meal scheme. The development and application of this method to new SUM data sets is difficult. It requires many inputs such as ambient temperature variations, meal clustering windows, and determination of thresholds.

5.4.2 Neural Network Based Algorithm

The SUM data processing method presented in this thesis draws upon existing literature and includes the use of neural networks for pattern recognition. This method of determining stove use that can be adapted to new SUM datasets with minimal inputs: one training and one target set. A manually predetermined subset of the raw data in an existing SUM dataset can be used as the training set (i.e. 50 days of SUM data from one user). Since there are variations in the temperature signatures that constitute a cooking event, it is favorable to include data in the training set that show heterogeneity of SUM events that should and should not be classified as stove use events. This will allow the neural net to properly distinguish between use and nonuse events since it has gained an understanding of various cases through the training set. The target set is a set of binary values corresponding to indices in the training set to indicate which regions should be classified as a stove use event. To develop the target set which is used to generate the neural network in this study, a pair of indices identifying the start and end times of cookstove use events in the training set was provided. This target must be created manually and may be informed by the use of a threshold or peaks.

Algorithm for identifying and calculating stove use duration:

1. Normalize data based on Minimum and Maximum Temperature in dataset
2. Create Training Set through manual identification of stove use events
3. Train, validate, and test neural network
4. Use neural network to evaluate SUM data

Normalization of the SUM data is performed first to address the variations in construction and attachment of the SUMs to the Makaa stoves as well as fuel type and ambient conditions which effect the burn characteristics. The Makaa stoves are locally manufactured by artisans and may not have a consistent heat transfer rate from fuel to the exterior of the stove. Additionally, the variations in the placement of the SUMs, size of steel tube, and strap size may introduce variations of minimum and maximum temperature recorded by the SUMs making direct comparison of SUM data from stove to stove difficult.

5.4.3 Performance of Neural Network Based Algorithm

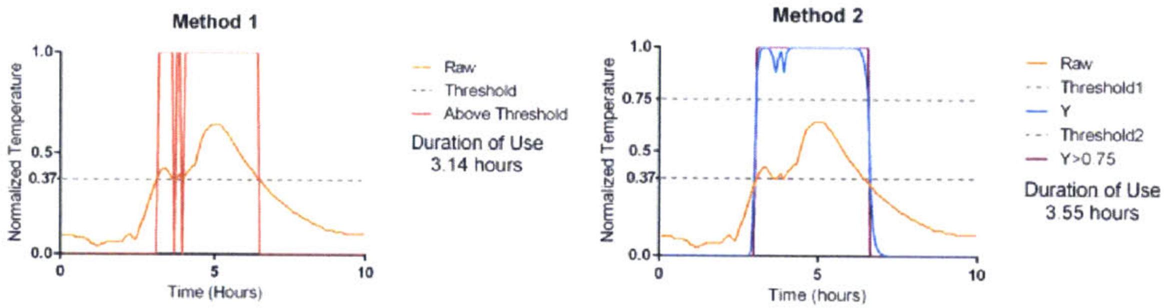

Figure 12: (left) Method 1 - Threshold based determination of stove use and duration, (right) Method 2 – Neural Net based determination of stove use and duration

Issue with threshold based processing algorithms is that they will underestimate the duration of use in the cases where the stove is used in a low heat setting or where multiple peaks are present. Although underestimation, as shown in the figure, of ~25 minutes seems low, it is accrued over the course of a day and results in an underestimate of the average usage time. The table presented below shows the difference in results when a pure threshold based identification is used versus the neural network over the course of 75 days. Both methods are benchmarked against the true value which was manually identified and used as the target set.

Table 1: Performance Comparison of SUM Processing Algorithms

Algorithm	Hours in Use	Error (Hours)	Error (%)
True Value (from target set)	362.75	-	-
Threshold Only	326.25	-36.5	11%
Neural Net	365.08	2.33	1%

Chapter 6: MEASURING ADOPTION OF IMPROVED COOKING TECHNOLOGIES IN UGANDAN HOUSEHOLDS

This improved cookstove adoption study was conducted in Soroti, Uganda with a collaboration between MIT's D-Lab and the Teso Women's Development Initiative (TEWDI Uganda), a local NGO. The improved cookstove examined in this study is the Makaa stove manufactured in Soroti by TEWDI's for profit partner Appropriate Energy Saving Technologies (AEST). The Makaa stove is sold in Soroti and surrounding areas through AEST for about 15,000 UGX or $4.50. In addition, AEST produces and sells briquettes made from biomass waste, typically peanut husks.

6.1 Study Design

The purpose of this study is to develop an understanding of user behavior, factors, and benefits which affect initial adoption and sustained use of improved cooking products from a market based intervention. Additionally, as a designer and manufacturer, AEST will be able to leverage this information to further understand its customers and create cooking products that cater to their needs. Qualitative and quantitative data was gathered from each of the study participants, in the form of:

1. Household interviews: for information regarding user preferences and behavior.
2. Remote monitoring: for unobtrusive measurement of product use.

Individual interviews lasting approximately 30 minutes were conducted with each participant household. Interviews were conducted with the primary cook of the household, which was often the oldest female. It was found that the primary cook was usually the decision maker in regards to purchase of the stove. After the interview a Sensen Stove Use Monitor (SUM) was attached to the Makaa stove. This study spans one year starting in August of 2015. The results of the first six months which constitutes the first phase of the study is discussed here.

6.1.1 Participant Selection

All participant households were residents of Soroti, Uganda at the start of the study. Soroti is located in the northeast of Uganda with an annual average temperature of 24.4 Celsius and annual precipitation of 1338.9 mm from about 126 days of rainfall annually [47].

TEWDI's involvement was beneficial to this research project because of their affiliation with AEST in addition to its location, and reputation within the community. Additionally, TEWDI had access to information about purchasers of Makaa stove as well as the means to connect with them. Therefore, guidelines for participant selection were jointly established and carried out by TEWDI. The AEST Makaa stove examined in this study was purchased by users with no subsidies or prompting from the research team. As an incentive to participate in the study, users were provided with a Greenlight Planet Sun King Eco solar lantern. Efforts were made to randomize selection of participants, but limitations in the size of AEST's consumer base as well as availability of participants resulted in a convenience sample.

6.1.2 Division of Participants

A total of 42 participant households were divided into three groups: non-users, new users, and existing users. Existing users are defined as users who had purchased the AEST Makaa Stove more than two months prior to the start of the study. Some existing users included in this study had purchased the stove up to one or two years before the start of this study. New users are defined as users who had purchased the stove less than two months prior to the start of the study. Most of the new users included in this study had purchased the stove one or two weeks before the start of the study, but a few households had been using the stove for about one month. The most commonly cited reasons for purchasing the Makaa stove by new users included product life, cost, portability, and energy savings. The non-users were participants who had not purchased or used to AEST Makaa stove. In the non-user group only 3 participant households owned an improved cookstove. A total of 11 participants constituted the non-user group, 20 in the new user group, and the remaining 11 in the existing user group. This discussion will focus on the new and existing user groups which is represented by 31 participants, because a SUM was installed in these households.

6.1.3 Participant Stove Ownership

It is important to note that in many cases the Makaa stove was not the only stove owned by a household. New users on average owned 2.9 stoves including the Makaa stove and existing users on average owned 2.27 stoves including the Makaa stove. Additional stoves could include a three stone fire, unimproved sheet metal stove (iron sheet *sigiri*), inbuilt traditional clay stove, or other improved cookstove. A three stone fire, a traditional style of cooking using an open fire, might be used because it is easy to set up and does not require any capital investment. An iron sheet sigiri costs approximately 6,000 UGX (~$1.80) and is made from sheet metal that is usually recycled from roofing material. From the survey it was found that of the 20 new users, nine had recently stopped using an iron sheet sigiri, citing high fuel consumption and poor durability. Traditional clay stoves are often built into the wall or floor of the kitchen of the household. Since they are custom built, their size, performance and durability are highly variable. Typically they fall in the tier 0 range of performance [43]. Other locally available improved cookstoves such as the Ugastove or Okelokuc, were also mentioned but less often than the other options.

6.2 Qualitative Survey Results

During the individual interviews, participants were asked about the positive and negative features of the Makaa Stove. The most frequently mentioned responses are summarized in Figure 13 and Figure 14. This portion of the survey was left as an open ended solicitation. Therefore, users could report none or more than one feature as a positive or a negative. Although the new user group and existing user group are made up of distinct users, a comparison can be made between them, which indicates a change in perception with sustained use.

6.2.1 Positive Features of Makaa Stove Reported by Participants

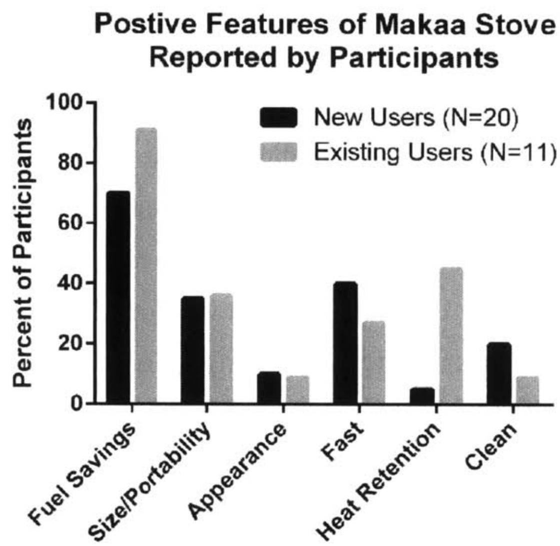

Figure 13: Positive Features of Makaa Stove Reported by Participants

Other infrequently mentioned positive features included: strength, safety, and ease of ash collection.

Fuel Savings

Of the positive features reported by the participants the most notable is fuel savings. Since a majority of the new users reported this as a positive feature it may have influenced their initial purchasing decision. Furthermore, a larger percentage of existing users also mentioned fuel savings as a positive feature indicating an increase in perceived fuel savings after purchase. As mentioned in other research studies, this data suggests that fuel savings is an important feature valued by consumers as they purchase and use the stove [44].

Heat Retention

There is a large difference (40%) between the new and existing users who reported heat retention as a positive feature. The main mass of the Makaa stove is composed of a cement mixture which holds the stove together. It also contributes to the high thermal mass of the stove as compared to mass manufactured stoves, such as the EcoZoom Jet, which is insulated with a low-density, glass fiber mat. The aspect of heat retention seems to be important to users as it likely is perceived to decrease the fuel requirement. The positive difference between the new and existing users indicates this is a probable motivator for sustained adoption of the Makaa stove.

Heat retention although is inversely related to the thermal efficiency. In other words, a stove with a high thermal mass will use more fuel to heat the mass of the stove rather than the intended cooking vessel thus decreasing its overall thermal efficiency. This trade-off between thermal mass and insulation quality should be further explored as it represents a conflict between user preference and performance.

Speed of Cooking

A smaller percentage of existing users as compared to new users reported the speed of cooking as a positive feature. This could mean that new users perceived the stove to be fast at the time of purchase, but after using the Makaa stove found that it did not meet their expectations. Alternatively, it could mean that over time the speed of cooking decreased due to degradations in the stove. Since this is a perceived characteristic it is difficult to attribute its meaning to either of these possible reasons. The final follow-up interviews will attempt gather more information regarding this aspect.

Cleanliness of Stove

One of the primary reasons for the promotion of improved cookstoves, such as the Makaa stove, is that it releases less harmful household air pollutants than a traditional stove. However, cleanliness of the stove in terms of both burn and emissions characteristics was among the least mentioned positive features for both groups. Some users have a stated value in the cleanliness of the stove, which they may have experienced as less soot on the pots and walls of their kitchen. Similar to the aspect of speed of cooking this may have been a motivation for purchase, but through use was found to not be as significant as expected. Another possible explanation for the low acknowledgement of this trait is that participants may not have been aware of the associated health risks.

6.2.2 Negative Features of Makaa Stove Reported by Participants

Negative features reported by participants were not as prevalent as the positive features. The weight of the stove and its durability are the largest reported drawbacks. It is possible that these two features are related. For example, a heavier stove may be dropped by the users more often and lead to damage. In any case, it is important to note these two features as they may be reasons for poor adoption or dis-adoption of the stove.

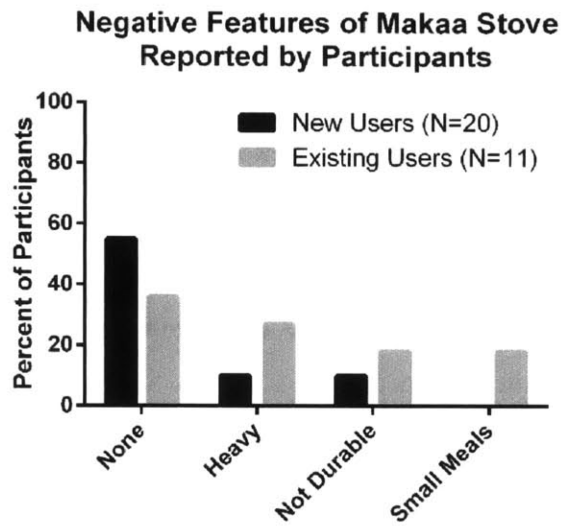

Figure 14: Negative Features of Makaa Stove Reported by Participants

Since the existing users cited negative features of the stove more than the new users, this may indicate that the issues become more apparent with use. In particular, existing users reported that cooking small meals was difficult (designated by the "Small Meals" label). However, no new users reported this issue indicating that it was encountered with sustained use.

6.3 Sensor Based Measurement of Stove Use

Analysis of usage trends from sensor measurements is presented in this section. Due to sensor malfunction, only data from 7 existing users and 14 new users was collected for data analysis. It appears that the malfunction may have been a result of faulty batteries and their close proximity to a cycling heat source, which lead to the SUM shutting off. Future iterations of this SUM will incorporate designs to further isolate the batteries and other electronic components from high heat exposure. The processing algorithm described in chapter 5 was used to determine the number of daily usage and cooking duration for Makaa stoves among new and existing users. A summary of data spanning the 130-day period of measurement is shown in Table 2. This summary does not capture temporal trends in usage for each group of users.

Table 2: SUM 130-day Summary of Trends

User Group	Average Use (hours)	Average # meals per day	Pearson Correlation Coefficient	p-value
Existing	6.7902	1.9846	0.3912	4.19E-06
New	6.2082	1.5374	0.5352	5.40E-11

Since there is a statistically significant positive correlation between the average duration of use and average number of meals per day, further analysis will consider only stove usage duration.

Figure 15 provides a visualization of the average and standard deviation of daily use for each participant group over the 130 days after the start of the study.

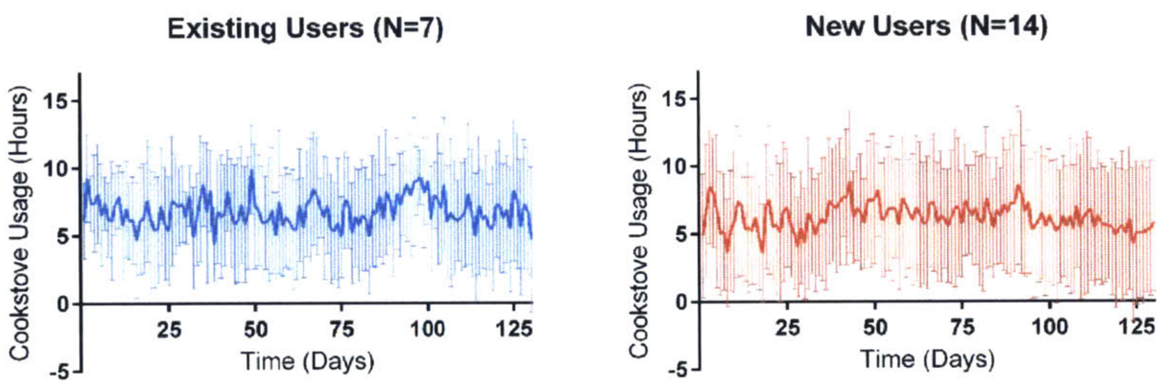

Figure 15: Existing and New User Daily Usage Trends

The large standard deviation present in both datasets is likely due to the fact that the installation of each SUM did not occur at the same time of day for every participant. Therefore, the start and end of each day as interpreted by the processing algorithm is different for each SUM dataset. For example, one SUM may have been installed at 9 AM for one user which would mean that one day for this participant constitutes a 24-hour period starting at 9 AM. Likewise, for another user the SUM may have been installed at 12 PM, which would mean that one day for this participant constitutes a 24-hour period starting at 12 PM. Although the total daily hourly usage for each household is captured in the variation in start time for the day may introduce variation of duration of use between users. Therefore, Figure 16 presents the same data after a 5-day average was computed to address the large variations.

6.3.1 Average Cookstove Use

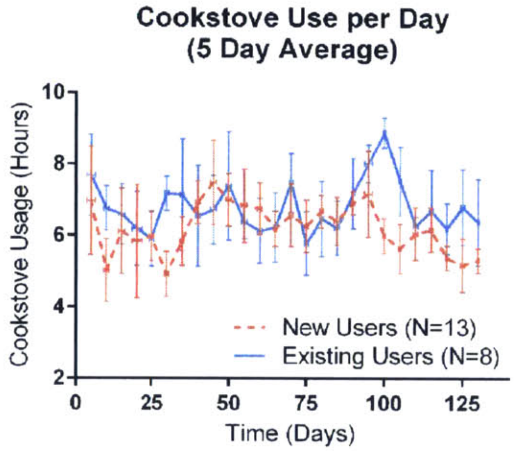

Figure 16: Cookstove Usage 5-day Average

Figure 16 shows that the daily cookstove usage of the new user group begins lower than the existing user. For the first 35 days the average usage of the new user group is 5.81 hours, while the average usage of the new user group is 6.77 hours. At 30 days the new user group usage begins to rise. Around 40 and 50 days after the start of the study the duration of cookstove usage of the new users resembles the usage of the existing users. Between days 35 and 75 the average usage duration for the new users was 6.646 hours, while the average usage duration for the existing users was 6.637 hours.

In the existing user group, we see a large increase in usage at day 100. This spike is not present in the new user data but we do see the standard deviation increase at around the same time. This large increase in use is expected to be the result of visitors or children returning home from boarding school, which was mentioned by the participants at the time of data retrieval

In Figure 16, at the start of the data collection we see large oscillations in usage for the new user group. For the first 25 to 30 days, usage fluctuates between 5 and 7 hours. This fluctuation is captured in the 5-day average as a standard deviation. Figure 17 shows the standard deviation in usage as a function of time. The standard deviation of the existing user group does not exhibit any temporal patterns and remains centered about 0.75 hours meaning that the pattern of their usage is more consistent. However, in the new user group the standard deviation of usage exhibits an exponential decaying behavior and settles close to the average of the standard deviation of the existing user group. The mean of the standard deviation of cookstove usage for the new user group after settling was 0.78 hours and the mean of the standard deviation of cookstove usage for the existing user group was 0.85 hours.

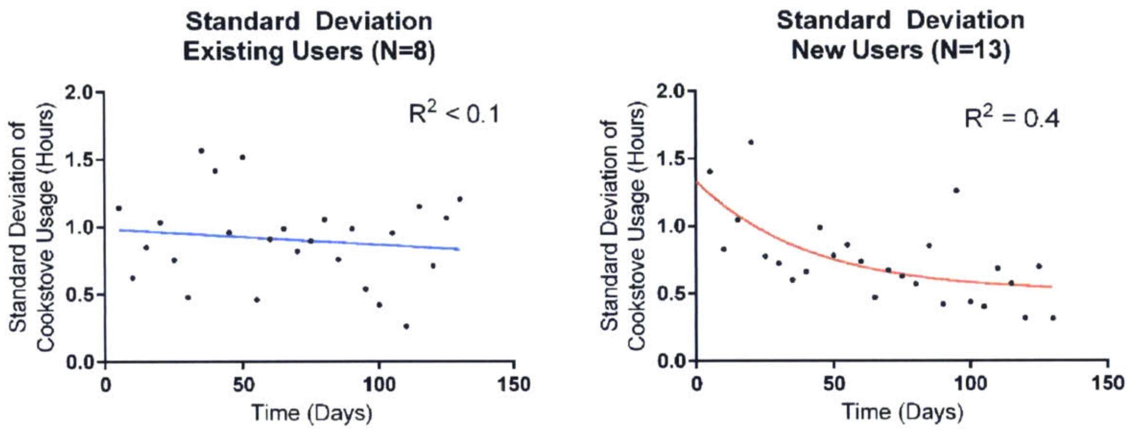

Figure 17: Standard Deviation of Cookstove Usage versus Time

6.3.2 Stoves in Use

Figures 15-17 aggregate the duration of cookstove usage for each group. In this section the duration of usage is used to evaluate if the stove has been used for that day. Since the duration of usage of the stove depends on the type of meal being prepared, this method provides a visualization, which is not sensitive to the type or number of meals cooked in a single day. Therefore, for the stove to be classified as "in use" the usage for a given day had to exceed one hour. Similar to Figure 16, a 5-day average of the fraction of stoves in use for each group was computed.

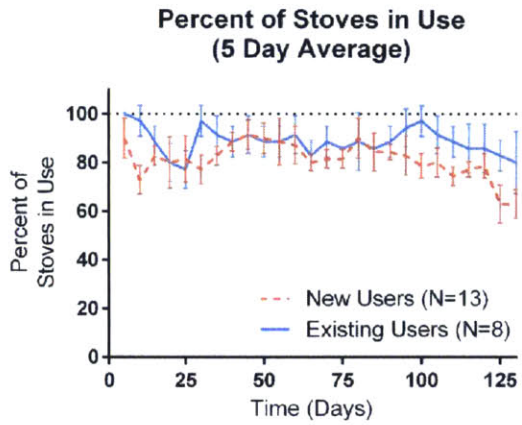

Figure 18: Percent of Stoves in Use 5-day Average

It is notable that in the existing user group there are frequent instances where 100 percent of the stoves in the participant group are in use. However, in the new user group those instances are much rarer. Overall, the trends for each user group appear to be similar. However, there is a departure in this similarity after about 80 days, for which no reason is currently available. The second follow-up to be conducted in August of 2016 will aim to further explain this discrepancy.

6.3.3 Adoption Trends

Figure 7 below plots the days that the stove is in use against the progression of the study.

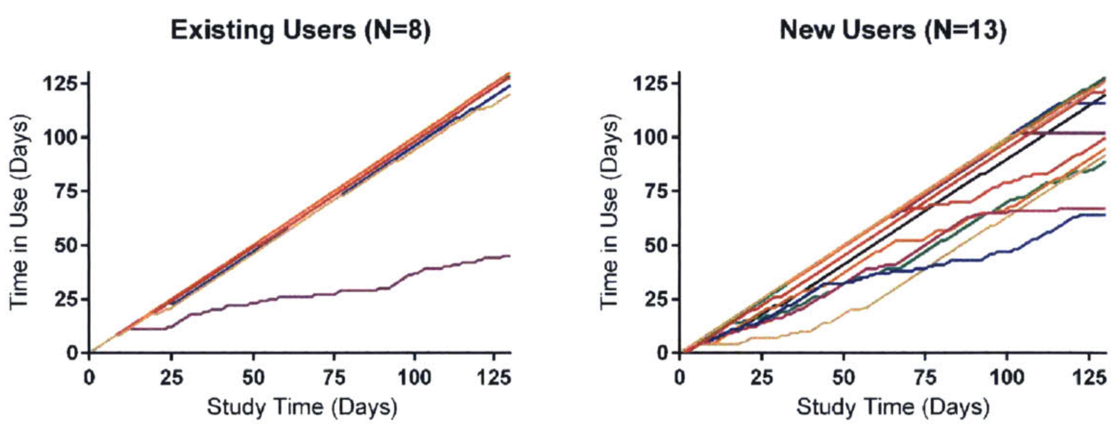

Figure 19: Adoption Trends During Sensing Period

It is apparent that aside from one user, members in the existing user group are consistently using the stove. The one outlier household had mentioned in the survey that their Makaa stove was primarily used for preparing small meals and tea, which may explain the lower rate of usage. In the new user group, a larger variation in usage is present. Conclusions from visual inspection of these plots are as follows. After 130 days: five users adopted at the beginning of the study, four users adopted after ~50 days, two users did not adopt, and the remaining two users dis-adopted after 110 days of consistent use.

Rogers' describes in the Diffusion of Innovations Theory the concept that an innovation permeates the marketplace in a normally distributed fashion with respect to the target consumers [48]. It is possible that the patterns evident in the adoption trends of the Makaa stove are artifacts of this theory.

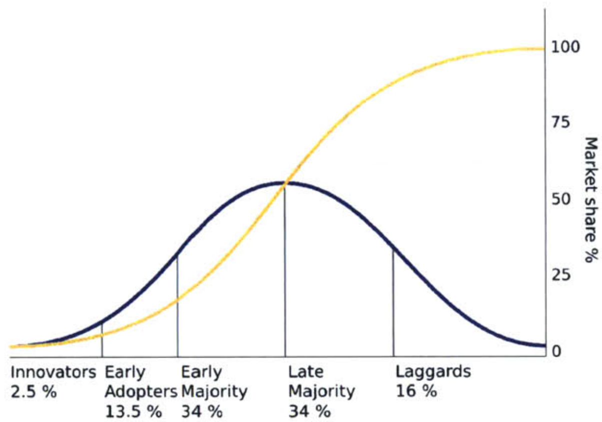

Figure 20: Everett Rogers' Diffusion of Innovation Model [48]

The existing users may fall into the early adopter category, while the new users may represent the early majority. Therefore, their rate and patterns to reaching sustained may be different. In addition, it is possible that the factors that influence adoption for the early adopters are different than the ones that would promote adoption for the early majority. As a result, is important to continuously monitor adoption through tools such as surveys and sensors to increase the success of a product, such as improved cookstoves.

6.4 Discussion of Results

The results from the first phase of this stove adoption study display strong adoption rates of the Makaa stove in Soroti, Uganda. Drawing on the four stages that contribute to the success of a product, it is apparent that there are positive characteristics as well as opportunities for improvement. Key factors in the design, such as the reduced fuel consumption as compared to traditional stoves differentiate the Makaa stove from existing solutions and exemplify its technical performance. Furthermore, the manufacturer has been able to leverage locally available materials to construct a robust stove. However, as demonstrated in the surveys conducted with the participants there is room for improvement in the areas of durability and weight. Moreover, the local presence of the manufacturer has allowed for ease of distribution to the target market. This continued presence may allow AEST to develop further services such as after-sales service to address issues such as durability. These factors combined with other difficult to identify factors such as biases introduced either in the interview or sensor installation phases contributed to the strong positive adoption rates of improved cookstoves in this community. Although, positive promotors of stove adoption have been identified in this study, it is important to recognize the conclusion reached by Puzzolo et al. that some factors are critical for success, but none guarantee it. Finally, such evaluations should be conducted on a regular basis in order to gather and inform further product iterations to gain additional market success.

Chapter 7: CONCLUSIONS

Product evaluation is the process by which the quality of product judged. Product quality is important to a range of stakeholders including but not limited to the designers and end users of a product. Evaluations of quality are conducted at various points as a product is transformed from an idea to reality. Therefore, the quality of a product can be scrutinized in four main stages: design, manufacturing, distribution, and consumer adoption. Each of the stakeholders involved with these stages will have a different perspective on the definition of quality. For example, a consumer would define the quality of a product based on how well a product meets their specific needs. However, a manufacturer's quality concerns are related to meeting the design specifications. With adequate quality in each of these steps a product can garner success in the marketplace. It is often difficult to separate these stages because of their integrated nature. Although there are sequential dependencies between these stages they often occur in an iterative fashion as issues are identified. This refers not only to full cycle product iteration but also to iterations between stages. For example, based on consumer feedback a product interface may be changed by the designer and a new revision of the product is produced. Or, iterations may occur between the manufacturer and designer to optimize for cost and speed of manufacturing. In any case, a product should be designed with the intent of catering to an end user's needs, but there are many challenges along the way. These challenges are particularly apparent in the case of product development for the developing world. Product evaluation is an important tool in characterizing those challenges and identifying approaches to appropriately address them.

For consumers in the developed world, there are a plethora of products that they may select from in a given product family. This has led to the creation of organizations such as Consumer Reports (CR) and the Consumer Product Safety Commission (CPSC), which conduct formal product evaluations. These entities act as third party unbiased advocates for the consumer to ensure that their interests, such as safety, are placed at the forefront of product development. Despite the focus on consumer interests, these two entities differ in their approach. One tests products against regulations while the other seeks to characterize the value of features present in a given product. To interpret the findings of quality and apply them practically it is important to understand the methodology used by these organizations. For regulatory agencies the required testing is often outlined in the form of laws. However, for an organization such as Consumer

Reports, the methodology is not explicitly described and is in fact guarded as a proprietary aspect of their business. However, published literature sheds light on the framework used to conduct these evaluations as well as its pitfalls. The goal of this methodology is to objectively quantify the quality of a product to the end user. A comparative rankings chart is constructed by selecting and testing a set of criteria relevant to a product family. The success and value of this organization can be seen in the fact that its annual revenue from subscriptions amounts to approximately $230,000,000.

With the growth of the global marketplace there is an increasing number of products designed for consumers in the developing world. Although regulatory agencies often exist in these nations, users still require information on product quality so that they can properly inform their purchasing decisions. This information is particularly important to the poor because of limited economic resources. The Comprehensive Initiative on Technology Evaluation (CITE) at MIT funded by a grant from the USAID global development lab has attempted to adapt this methodology to conduct evaluations of poverty alleviating products in the developing world. However, in the process of conducting the first evaluation on personal solar based lighting products it was found that the adaption of the Consumer Reports methodology to developing world products is challenging. The issues stem from two key assumptions: market homogeneity and ease of data collection. Unlike the developed world, the markets in the developing world are heterogeneous. In other words, every product is not ubiquitous. Not only are the distribution networks not as extensive, but the user base is not well understood in terms of consumer preference. Therefore, it is unclear which products of a given product family should be evaluated if not all are available everywhere. As a result, the criteria for evaluation is difficult to construct, which may increase the cost and complexity of data collection. Either all of the possible products must be tested, or a limited scope must be chosen in which case the data will be irrelevant or incomplete to some consumers and regions. Furthermore, the costs and complexity associated with lab testing are tremendous. Since the usage patterns of a product are difficult to identify it is laborious to emulate field conditions or conduct accelerated life testing. However, recent improvements in low power electronics and computing power are enabling the adaptation of instrumentation to the field setting. In addition, recent studies have shown that traditional survey based collection of data on usage can be biased and provide misleading information. For product developers this can result in pursuing the wrong avenues for future product iterations. Therefore, field based sensing may be a promising alternative to lab testing as continuous data on performance can be gathered without investments in capital equipment. However, challenges in deploying sensing systems at scale in a cost-effective manner must still be overcome.

The complications in adapting the Consumer Reports methodology highlight the fact that due to the consumer biased perspective of quality in the developed world models, emphasis has been placed on the design and manufacturing stages. However, products that are created for the developing world face significant challenges in the final two phases: distribution and adoption. Which is due in part to the intricacies of the marketplace and other socioeconomic barriers. Therefore, the burden of product quality evaluation falls to the institutional stakeholders that provide a product to consumers in an effort to improve their livelihood. The framework of the four stages presented previously places less emphasis on the functional performance of the product and prioritizes creation of a product that caters to the needs of the user.

CITE employs a 3S methodology to evaluate each product on the premise of suitability, scalability and sustainability. These three categories essentially reiterate the four stages outlined previously, but leave manufacturing as an ambiguous step which may fall between suitability and scalability. In practice, it has been difficult to conduct these evaluations in a holistic manner. This may be to some degree due to the overlap between the various stages or since an evaluation of all the stages is not necessary for all products.

Further efforts should focus on determining a financially viable method of conducting holistic product evaluation developing world products: that combines the design, manufacturing, distribution and adoption stages. This may involve shifting the audience from the end users to non-governmental organizations who procure these products for developing world users or an independent contracting agency to report this material to a product developer. It is important for these organizations to provide products that meet the end user's needs to develop a positive relationship with the communities and their funders, enabling them to expand their work further and create a positive impact. It is my opinion that these evaluation results need not take the form of the comparative ratings chart such as the one that Consumer Reports provides. In some cases, strict adherence to this chart form can be onerous, misleading, and too simplistic. Often the facets that are worth evaluating are not easily representable in this chart configuration.

A case study examining improved cookstoves is used to illustrate each of the four stages (design, manufacturing, distribution, adoption) of a product's success. Dissemination of improved cookstoves is a solution that has been pursued since the 1970s in response to issues such as household air pollution, deforestation, and household energy security. In order to narrow the discussion, the case of biomass based charcoal cook stoves is presented. With a review of the relevant literature it is apparent that a large focus has been dedicated to design and technical performance, while less attention has been granted to the other three stages. However, these phases are important to address and improve upon in order to take positive steps in addressing the concerns presented by household cooking technologies. Evaluation in the other three stages can identify possibilities for improvements that are feasible to implement, and this case study demonstrates that there is often not one superior avenue. For example, although high-volume manufacturers can benefit from quality control practices and use of exotic materials, local manufacturers can benefit from their local presence in understanding their customers and providing support to users through after sales service which has shown to be an important aspect of promoting sustained use of improved cookstoves.

The role of field based sensing has been identified as a promising method to conduct developing world product evaluations. In Chapter 5, the technical construction of a data logging and analysis tool for measuring adoption of improved cookstoves is described. Researchers currently using sensor based methods have outlined the need for a common algorithm which is easy to implement. Therefore, a new method has been devised to process temperature data using neural networks. This method allows a consistent output that does not require a large number of conditional clauses or inputs. As the use of sensors for field testing and monitoring of products grows, these techniques will become vital since the size of datasets will subsequently grow and gathering meaningful results will increase in complexity.

Finally, the results of an adoption study conducted in Soroti, Uganda in collaboration with a local NGO, Teso Women's Development Initiative (TEWDI) is presented. The study uses limited surveys and the continuous sensor data logging platform, mentioned previously, to examine the adoption rates of an improved biomass charcoal stove. The stove in consideration is produced locally by the for-profit partner of TEWDI - Appropriate Energy Savings Technologies Uganda (AEST). Participants were separated into two groups: a new user group and an existing user group. Trends in usage were compared and contrasted between the groups. In this study, it is apparent that sensors can be a cost effective means of gathering information about adoption rates. Additionally, when a market based intervention is combined with a locally manufactured stove and stove use monitoring sensors a high rate of adoption is observed among users. It is possible that bias may have been introduced by the presence of the sensors, which should be further explored. Nonetheless, the use of sensors in a field setting presents many benefits in understanding not only product adoption but gathering indicators of product performance. Data related to adoption may be particularly useful for NGOs seeking to implement stove programs so they may promote the use of cleaner cooking technologies. In addition, this data may also be useful for distributors and manufacturers as they would be able to learn the failure rates, time to failure, and periods of non-use related to their product. In this specific case, the manufacturer was able to provide after sales service to the users who had damaged stoves based on observation during follow-ups. This appears to be a critical parameter in ensuring adoption and sustained use of improved cook stoves. However, it should be noted that the methodology employed in this study is not the only way that improved cook stoves can be introduced into communities.

Appendix A: Sensen Stove Use Monitor Design

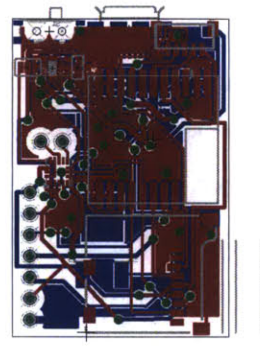

Figure 21: Sensen Stove Use Monitor Printed Circuit Board

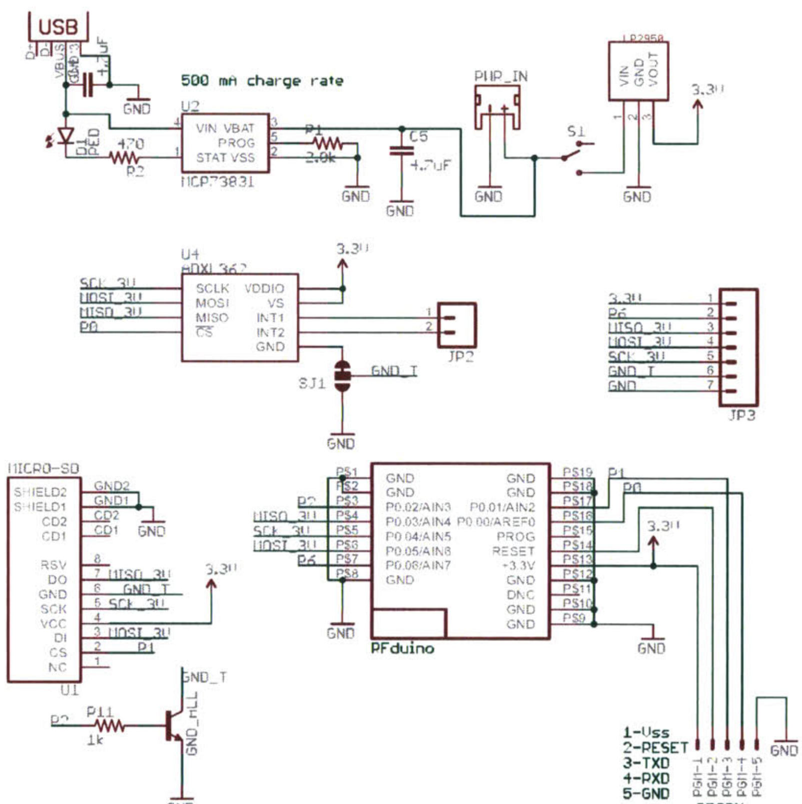

Figure 22: Sensen Stove Use Monitor Schematic

Appendix B: Open Access to Files and Data

Due to space constraints all of the MATLAB files and data used and processed in this thesis can be found here: http://tinyurl.com/hot362c. For information on adapting these files for further use see Appendix C.

Appendix C: Stove Use Monitor Neural Network Based Processing Algorithms

Instructions:

1. Generate Training Set: Run 'generate_training_set.m' in Appendix C.1. This script will reference data in 'training_indices.mat' and 'sum01_60day.mat'.
2. Train Neural Network: Run 'sumTrain.m' in Appendix C.2. This script will reference data in 'sum_training_set.mat' and 'sum_target_set.mat' generated in the previous step.
3. Process Data from one SUM: Run 'neural_run_one.m' in Appendix C.3. This script will call 'neural_test_day.m' (Appendix C.4), 'load_SUM_data.m' (Appendix C.5), and 'myNeuralNetworkFunction.m' (Appendix C.6).
4. To process SUM data from multiple sets of SUMs simply modify 'neural_run_one.m' to look like 'neural_run_new.m' (Appendix C.7) with the appropriate file naming scheme. Additional processing and visualization scripts are included in 'neural_run_new.m' and here: http://tinyurl.com/hot362c.

C-1 Generate Training Set: 'generate_training_set.m'

```
clear all
close all
clc

%This script will generate the training set required for the machinie
%learning algorithm based on 60 days of predetermined SUM data. This data is
provided here:

load('sum01_60day.mat');
ndays = 60;
time_hour = sum01_60day(:,1);
dayn_data = sum01_60day(:,2);

threshold = 0.37; %based on already normalized data
load('training_indices.mat') %for threshold 0.37
start_event = training_indices(:,1);
end_event = training_indices(:,2);
threshold2 = ones(length(start_event),1).*threshold;

beg = max(find(time_hour < start_event(1)));
target = zeros(1,beg);
fin = min(find(time_hour > end_event(1)));
target = [target ones(1,fin-beg)];
next = fin;

for i=1:length(start_event)-1
    beg = max(find(time_hour < start_event(i+1)));
    target = [target zeros(1,beg-next)];
    fin = min(find(time_hour > end_event(i+1)));
    target = [target ones(1,fin-beg)];
    next = fin;
end
remain = length(time_hour)- next;
target = [target zeros(1,remain)]';

figure()
plot(time_hour, dayn_data)
hold on
refline(0,threshold)
plot(start_event,threshold2,'go')
plot(end_event,threshold2,'go')
xlim([-5 max(time_hour)+5])
ylim([-0.1 1.1])
plot(time_hour(1:length(target)),target)

frac_on = sum(target)/length(target); %fraction of time that stove is in use
tot_hours = frac_on*ndays*24; % total duration of use per day
avg_use = tot_hours/ndays

training_indices(:,1) = start_event;
training_indices(:,2) = end_event;
save('training_indices.mat','training_indices')
save('sum_training_set.mat','dayn_data')
save('sum_target_set.mat','target')
```

C-2 Train Neural Network: 'sumTrain.m'

```
clear all
close all
clc

load('sum_target_set.mat')
load('sum_training_set.mat')

% Solve a Pattern Recognition Problem with a Neural Network
% This script assumes these variables are defined:
%   dayn_data - input data.
%   target - target data.

x = dayn_data';
t = target';

% Choose a Training Function
% For a list of all training functions type: help nntrain
% 'trainlm' is usually fastest.
% 'trainbr' takes longer but may be better for challenging problems.
% 'trainscg' uses less memory. Suitable in low memory situations.
trainFcn = 'trainscg';  % Scaled conjugate gradient backpropagation.

% Create a Pattern Recognition Network
hiddenLayerSize = 10;
net = patternnet(hiddenLayerSize);

% Setup Division of Data for Training, Validation, Testing
net.divideParam.trainRatio = 70/100;
net.divideParam.valRatio = 15/100;
net.divideParam.testRatio = 15/100;

% Train the Network
[net,tr] = train(net,x,t);

% Test the Network
y = net(x);
e = gsubtract(t,y);
performance = perform(net,t,y)
tind = vec2ind(t);
yind = vec2ind(y);
percentErrors = sum(tind ~= yind)/numel(tind);

% View the Network
view(net)

% Plots
% Uncomment these lines to enable various plots.
%figure, plotperform(tr)
%figure, plottrainstate(tr)
%figure, ploterrhist(e)
%figure, plotconfusion(t,y)
%figure, plotroc(t,y)

save net
```

C-3 Run Neural Network Algorithm for single SUM file: 'neural_run_one.m'

```
clear all
close all
clc

%This script will process data from one file, in this example: 'sum01.xlsx'
%data in this file should be formatted with the first column containing
%time data and the second column containing temperature data. To process
%multiple files simply modify this script to call 'neural_test_day.m' for
%each file.

ndays = 130; %define total number of days in file
total_points = ndays+30;
day_dur = zeros(total_points,1);

textFileName = 'sum01.xlsx'; %example

[avg_use day_dur(:,1)] = neural_test_day(textFileName,ndays,total_points);

figure()
plot(day_dur)

avg_day_dur = sum(day_dur)/ndays
std_day_dur = std(day_dur)
```

C-4 Function to calculate hours of use of a given SUM file: 'neural_test_day.m'

```
function [avg_use, day_dur,avg_meals, meals] = neural_test_day(filename, days
,total_points)

%Will calculate the average hours of use, average number of meals over the
%full length of time in the file. Additionally, will calculate the duration
%per day and number of meals per day over the full length of time in the
%file

[time_day, norm_data, ndays] = load_SUM_data(1,days,filename,2);

%%
%run this for all all days present in the data set
for d = 1:ndays-1
    %for d = 1:3

    %load day "d" data
    if(d-1 == 0) % start furst day at index 1 not 0
        start_ind(d,1) = (1);
        end_ind(d,1) = find(time_day == d)-1;
    else
        start_ind(d,1) = find(time_day == d-1);
        end_ind(d,1) = find(time_day == d)-1;
    end
    dayn_data = norm_data(start_ind(d):end_ind(d));
    time_hour = 1:length(dayn_data);
    time_hour = (time_hour.*5)/60; % corresponding time vector (hours)

    %Run neural net
    [Y,Xf,Af] = myNeuralNetworkFunction(dayn_data);

    use = Y>0.4; % classify as "in use" if neural net has calc 40%
probability
    frac_on = sum(use)/length(use);%fraction of time that stove is in use
    tot_hours = frac_on*24; % convert to hours

    day_dur(d,1) = tot_hours; %total duration of cooking for day i

    % count the number of meals in the day by counting transitions from in
    % use to out of use and vice versa
    zero_to_one = 0;
    one_to_zero = 0;
    for i=1:length(use)-1

        if(use(i)<use(i+1))
            zero_to_one = zero_to_one+1;
        end

        if(use(i)>use(i+1))
            one_to_zero = one_to_zero+1;
        end

    end
```

```
    if(zero_to_one == one_to_zero)
        meals(d,1) = zero_to_one;
    else
        meals(d,1) = (zero_to_one + one_to_zero)/2;
    end
    meals(d,1);
end

avg_meals = sum(meals)./ndays

avg_use = sum(day_dur)./ndays

day_dur = padarray(day_dur,total_points-length(day_dur),'post');
meals = padarray(meals,total_points-length(meals),'post');
```

C-5 Function to load and normalize SUM data: 'load_SUM_data.m'

```
function [time_day, dayn_data, ndays] =
load_SUM_data(start_day,end_day,filename,col)

% load data from SUM data set "filename"
% starting at "start_day" ending at "end day
% then normalize the data
% for example load_SUM_data(1,100,sum01.xlsx,2)
% will load data from file sum01 from days 1 to 100 and all
% temperature data is in column 2 of file sum 01

num = xlsread(filename);

%normalize data 0 to 1
data = num(:,col); % SUM data is located in second column
norm_data = data - min(data);
norm_data = norm_data./max(norm_data);

%create time vector
time = 1:length(data); % number data points
days = (time.*5)/60/24; %index of days in set

%if end_day is larger than number of days in data set
if end_day > floor(max(days))
    end_day = floor(max(days)); %max days in data set
end

%load day "d" data
if(start_day == 0) % start furst day at index 1 not 0
    start_ind = 1;
else
    start_ind = find(days == start_day);
end

if(start_day<end_day)
    end_ind = find(days == end_day)-1;
    dayn_data = norm_data(start_ind:end_ind);
    time_day = 1:length(dayn_data);
    time_day = (time_day.*5)/60/24; % corresponding time vector (hours)
    time_day = time_day';% make into column vector
else
    disp 'start_day must be less than end_day'
end

ndays = end_day-start_day-1;
end
```

C-6 Function to determine whether a stove event should be classified as in use or not: 'myNeuralNetworkFunction.m'

```
function [Y,Xf,Af] = myNeuralNetworkFunction(X,~,~)
%MYNEURALNETWORKFUNCTION neural network simulation function.
%
% [Y] = myNeuralNetworkFunction(X,~,~) takes these arguments:
%
%   X = 1xTS cell, 1 inputs over TS timesteps
%   Each X{1,ts} = Qx1 matrix, input #1 at timestep ts.
%
% and returns:
%   Y = 1xTS cell of 1 outputs over TS timesteps.
%   Each Y{1,ts} = Qx1 matrix, output #1 at timestep ts.
%
% where Q is number of samples (or series) and TS is the number of timesteps.
%
% If issues arise using this function it can be regenerated by using the
%MATLAB Statistics and Machine Learning Toolbox

load net

% ===== NEURAL NETWORK CONSTANTS =====

% Input 1
x1_step1_xoffset = 0;
x1_step1_gain = 2.31578947368421;
x1_step1_ymin = -1;

% Layer 1
b1 = [13.999344395461906;10.892840322036337;-7.7906147596018354;-
4.6718683943315122;-1.5217264059075108;-1.7381898536869469;-
2.8435856594463105;-7.3148646482078918;10.850142853549933;-
14.001048420167836];
%IW1_1 = [-14.000608467645057;-
13.997119409979611;13.993020843309846;13.998686630421137;14.001707811995219;-
14.109403583586364;-14.145265573806167;-
14.241243198355331;14.027479765983257;-13.999080455769633];
IW1_1 = net.IW{1};

% Layer 2
b2 = 0.10662436932486176;
%LW2_1 = [-0.77715393854061721 0.51962835906347371 -0.24207102181243392
1.5066289981381573 0.32470159165046641 -2.6363025206269501 -
1.0341091040741468 -2.6719164581081922 0.5943241767276024
0.092099536871618606];
LW2_1 = net.LW{2,1};

% ===== SIMULATION ========

% Format Input Arguments
isCellX = iscell(X);
if ~isCellX, X = {X}; end;

% Dimensions
```

```
TS = size(X,2); % timesteps
if ~isempty(X)
    Q = size(X{1},1); % samples/series
else
    Q = 0;
end

% Allocate Outputs
Y = cell(1,TS);

% Time loop
for ts=1:TS

    % Input 1
    X{1,ts} = X{1,ts}';
    Xp1 =
mapminmax_apply(X{1,ts},x1_step1_gain,x1_step1_xoffset,x1_step1_ymin);

    % Layer 1
    a1 = tansig_apply(repmat(b1,1,Q) + IW1_1*Xp1);

    % Layer 2
    a2 = logsig_apply(repmat(b2,1,Q) + LW2_1*a1);

    % Output 1
    Y{1,ts} = a2;
    Y{1,ts} = Y{1,ts}';
end

% Final Delay States
Xf = cell(1,0);
Af = cell(2,0);

% Format Output Arguments
if ~isCellX, Y = cell2mat(Y); end
end

% ===== MODULE FUNCTIONS ========

% Map Minimum and Maximum Input Processing Function
function y = mapminmax_apply(x,settings_gain,settings_xoffset,settings_ymin)
y = bsxfun(@minus,x,settings_xoffset);
y = bsxfun(@times,y,settings_gain);
y = bsxfun(@plus,y,settings_ymin);
end

% Sigmoid Positive Transfer Function
function a = logsig_apply(n)
a = 1 ./ (1 + exp(-n));
end

% Sigmoid Symmetric Transfer Function
function a = tansig_apply(n)
a = 2 ./ (1 + exp(-2*n)) - 1;
end
```

C-7 Run Neural Network Algorithm for multiple SUM files: 'neural_run_new.m'

```
clear all
close all
clc

%This script will load and run the neural network algorithm for
%new participants

%These numbers correspond to the file number for New Users
New = [2,6,7,9,13,14,16,18,20,24,25,28,29,30];
count = 1;

total_points = 160;
day_dur = zeros(total_points,length(New));
avg_use = zeros(1,length(New));
meals = zeros(total_points,length(New));
avg_meal = zeros(1,length(New));
ndays = 150;
len_test = 130;

%load multiple files
for i=1:length(New)

    sum_num = New(i);
    if(sum_num<10)
        textFileName = ['sum0' num2str(sum_num) '.xlsx'];
    else
        textFileName = ['sum' num2str(sum_num) '.xlsx'];
    end

    if exist(textFileName, 'file')
        [textFileName ' exists']
        [avg_use(1,count), day_dur(:,count),avg_meal(1,count),
meals(:,count)] = neural_test_day(textFileName,ndays,total_points);
        count = count+1;
    else
        [textFileName ' does not exist']
    end
end

%Begin processing
avg_day_dur = sum(day_dur,2)./(count-1);
std_day_dur = std(day_dur,0,2);

nbins = 15;
[n,xout] = hist(avg_day_dur,nbins);

figure()
bar(xout,n)
hold on
plot([mean(avg_day_dur) mean(avg_day_dur)],[0 max(n)],'-rx')
title('Average Duration of Use per Day')
xlabel('Hours per Day')

avg_meals = sum(meals,2)./(count-1);
```

```
std_meals = std(meals,0,2);

nbins = 15;
[n,xout] = hist(avg_meals,nbins);

figure()
bar(xout,n)
hold on
plot([mean(avg_meals) mean(avg_meals)],[0 max(n)],'-rx')
title('Average Meals per Day')
xlabel('Hours per Day')

figure()
plot(1:length(avg_day_dur),std_day_dur)
xlim([0 len_test])
hold on

title('Standard Deviation of Duration of Use per Day (New Users, n=8)')
xlabel('Day')
ylabel('Hours of Use per Day')

%% save files
n_all_day_dur = day_dur;
n_meals = meals;
save('all_new_user_data.mat','n_all_day_dur','n_meals')

n_avg_day_dur = avg_day_dur;
n_std_day_dur = std_day_dur;
n_avg_meals = avg_meals;
n_std_meals = std_meals;
save('new_user_data.mat','n_avg_day_dur', 'n_std_day_dur','n_avg_meals',
'n_std_meals')
```

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