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Balancing Technical and User Objectives in the Design of Improved Biomass Cookstoves for Developing Regions of the World

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ABSTRACT

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Over the past decade a large amount of research has been dedicated in academic literature to improving the technical capabilities of improved cookstoves; primarily the performance efficiency and reduction of emissions. Unfortunately, as published literature has highlighted, the trade-offs that result from placing such a concentrated emphasis on these technical objectives is that improved cookstoves lack the same level of usability as traditional cookstoves. Thus, users often return to using their traditional stoves and the potential impact of the improved cookstoves is never fully realized. In order for improved cookstoves to have greater impact, there must be better balance between the two competing design objectives of technical capabilities and usability. This research explores the challenges and benefits associated with achieving the appropriate balance, and provides guidance on how to more effectively achieve this. A list of the most common customer needs from around the world is provided for cookstoves. Interestingly, there are needs that are common to all cookstove users (global needs), and needs that apply to only a subset of users (local needs). Due to the diversity of such needs, there are many unique challenges that come with trying to satisfy these in the design process. A design methodology is presented that accounts for these challenges and helps balance the competing design objectives. This methodology is demonstrated through the modification of a traditional cookstove used in the Tambogrande region of Peru. This modification includes an inexpensive set of pot skirts that integrates directly with the traditional stove. These pot skirts allow for varying sizes and number of pots, and the use of traditional fuels. Laboratory testing, using the Water Boiling Test (WBT), identified the skirts' technical improvements: 41.7% increased thermal efficiency, 32.7% decreased fuel consumption, 28.8% decreased time to boil. Field testing was performed to determine the pot skirts acceptance and compatibility with the traditional cookstoves, with over 75% of the participants recognizing some type of benefit. Although the technical improvements of these pot skirts are less than other cookstoves on the market, the higher levels of usability are likely to lead to a more positive end-user reaction, which could potentially lead to higher rates of adoption and impact. Though this research is primarily focused on the application of improved cookstoves, the need for more balance between technical and user objectives is applicable to nearly all products being designed for the developing world.

Keywords: improved cookstoves, developing world, design, user needs

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CHAPTER 1. INTRODUCTION

Over the course of the past decade, significant effort and attention has been given to the advancement of improved biomass cookstoves for the developing world [1–6]. These improvements are motivated by the fact that nearly 3 billion people worldwide still cook using open fires or biomass cookstoves, in which they burn wood, charcoal, and other solid fuels [7]. Biomass cookstoves are a significant contributor to current global warming problems; contributing 22% of the global black carbon emissions, compared to just 7% from the burning of fossil fuels [8]. With nearly 3 million people dying each year due to the harmful effects of burning biomass [7], improved cookstove programs have primarily focused in the past on reducing indoor air pollution, greenhouse gases, and the amount of biomass fuel that is consumed. As a result of these efforts, improved cookstoves have made significant progress in achieving high levels of efficiency and high standards of cleanliness.

Despite the technical capabilities of these improved cookstoves, end users have generally adopted and used them at surprisingly low rates [9]. Jan et al. report adoption rates of less than 20% for a random study of 100 households in rural northwest Pakistan [10]. Pine et al. report an even smaller adoption rate of 15% for a particular cookstove project in Mexico [11]. Other studies have found similar results for various parts of the world [12, 13]. Examples such as these demonstrate that an improved cookstove's ability to burn cleaner and more efficiently does not guarantee its adoption.

The lack of adoption following initial stove dissemination could be a result of many factors. Troncoso et al. identified several social factors that can impact adoption rates, such as occupation, income, or education level [14]. Furthermore, a community's economics, government, distribution methods, and prevailing biases towards improved cookstoves also have the potential to affect adoption rates [11, 12, 15, 16]. However, in the more recent past, several researchers have begun to observe and emphasize one particular reason for the low adoption rates — the end user needs not being sufficiently considered in the design of the improved cookstove [11,12,17–21]. As expressed by Urmee and Gyamfi, "many of the past biomass cookstove programs have failed due to a lack of proper understanding of the needs of the people who use this technology" [5].

Thus we see that improved cookstoves must achieve two objectives in order for lasting impact to occur. First, they must provide technical performance improvements (i.e. decreased smoke, higher efficiency, etc). Second, they must achieve high levels of adoption, which we believe is directly tied to its level of usability. Unfortunately, the usability of the cookstove and its technical capabilities are often competing design objectives. Due to the nature of the problem, designers and engineers have primarily optimized cookstoves for the latter.

In this research, we propose and explore a different design approach than that which has been promoted in the past: *If the design of improved cookstoves are primarily optimized for usability, while having at least some technical improvement over traditional stoves, then greater impact can be achieved.* In order to explore and establish this approach, answers to the following research questions will be provided.

1. In the context of improved cookstoves, what does it mean to design for usability?
2. What barriers/challenges have prevented designers from being successful at designing more usable cookstoves?
3. What are the end user needs that should be considered with a usability centered approach?
4. How do end user needs vary across regions, within communities, and within households?
5. How should the design process be adjusted in order to overcome these challenges and achieve a more user friendly result?
6. When using this modified design process, how are the resultant cookstoves different, and do these cookstoves have a greater chance for adoption and subsequently higher impact?

While this thesis is primarily focused on the topic of improved cookstoves, it is also applicable to a more general audience. The principles introduced in this research apply to nearly all new products that are being designed for the developing world and have intentions to provide some type of social, financial, or environmental benefit.

1.1 Thesis Overview

This thesis is divided into five main parts, or chapters. It is beneficial to give a brief overview of these chapters and how it ties into the overall objectives of this research.

Chapter 2: Background Research. This chapter is dedicated to providing a brief history of improved cookstoves as well as the recent motivation behind this research. Additionally, the term "usability" is defined in the context of improved cookstoves.

Chapter 3: Identifying End User Needs. As introduced earlier in this chapter, other authors have noted the frequent misidentification of user needs in previous cookstove development efforts. In attempts to help researchers avoid similar mistakes in the future, this chapter identifies what we believe to be the most common end user needs that should be considered during the design process.

The majority of the content in this chapter was originally published in the IEEE Global Humanitarian Technology conference in San Jose, California [22].

Chapter 4: Regional, Community, and Household Factors that Determine End User Needs. One of the common pitfalls that befalls designers and engineers is assuming that the end user needs are similar for everyone within the targeted user base. This is not the case. There exists a variety of regional and community factors that cause different households to have completely different needs. In addition, there exists many variables that cause the same household to have different needs throughout the course of a day or year. In order to achieve higher levels of usability, designers need to understand what these factors and variables are, and if they are relevant to their targeted users.

A significant portion of this chapter was also published in the IEEE Global Humanitarian Technology conference in San Jose, California [22].

Chapter 5: Tailored Design Methodology. We have found that simply understanding what the customer needs are is only one step in the greater process of gathering, interpreting, validating, and using customer needs to shape the way improved cookstoves should be designed. Unfortunately, following a standard design process in a foreign and unfamiliar developing world setting is difficult. In this section, a new design methodology is presented specifically for improved cookstoves.

The majority of the content in this chapter was taken from the journal submission to the International Journal of Product Development (under review) [23].

Chapter 6: Preserving Usability in a Peruvian Cookstove - A Case Study. In this chapter, the results from applying the principles and methodologies of this research are presented. This case study focuses on optimizing the usability of an improved cookstove intended for the Tambogrande region of Peru. Results are shared regarding the technical performance of the design modification, along with customer acceptance and perception data from field testing.

Significant portions of this chapter were originally published in the ASME International Design Engineering Technical Conference [24], as well as in the The Journal of Development Engineering [23].

Chapter 7: Conclusion. This chapter will be dedicated to discussing the implications and value of the research presented in this body of work. Main results will be summarized, key contributions highlighted, and recommendations for further research will be provided.

CHAPTER 2. BACKGROUND RESEARCH

2.1 History of Improved Cookstoves

The dissemination of improved cookstoves has been of interest since the 1970's. Initial motivation for the development of improved cookstoves was to preserve the rapidly depleting forests [25]. In the 1980's, the goal of improved cookstoves shifted to improving the quality of indoor air and several large scale cookstove programs followed soon thereafter. Most impressively was the Chinese National Improved Stove Program that installed 129 million improved cookstoves in rural households [26]. In the late 1990's and early 2000's, interest in improved cookstoves remained high with over 95 improved cookstove programs emerging [27]. More recently, in 2010 the United Nations (U.N.) announced the formation of the Global Alliance for Clean Cookstoves – an international coalition with the goal to bring improved cookstoves to 100 million households by the year 2020.

Hundreds of different improved cookstoves have been developed in the past decade in attempts to decrease fuel usage and improve air quality. Literature contains hundreds of articles describing the designs, the benefits, the impact, and also the limitations of these improved cookstoves. Areas of the world that are most frequently referenced in literature include China, India, Kenya, Mexico, and Bangladesh as well as other various regions. In addition to the impact that these stoves have on specific target populations, several authors have also published articles comparing the performance of the most popular stoves. For instance, MacCarty et al. tested and compared the fuel use, time to boil, energy use, and emissions of the 50 most common cookstoves [28]. Other authors have done similar comparisons at a smaller scale [29]. The Global Alliance for Clean Cookstoves also maintains a database of testing results for the most popular improved cookstoves [30]. The majority of the improved cookstoves tested performed better than the traditional three stone fire, however there were several that did not, thus demonstrating that because a cookstove is given the label of "improved" does not necessarily mean it is superior to the traditional cooking methods in efficiency, cost savings, and especially ease of use.

2.2 Design of Improved Cookstoves

Designing a clean burning and efficient cookstove is a difficult task due to the large amount of variables. Fuel type, moisture content, cost, meal size, desired firepower, and cooking utensil size are examples of variables that must be considered. There also often exists conflicting interests between the usability of a stove and the efficiency of the stove. For instance, users typically want to be able to stoke the fire with large pieces of wood but this comes at the expense of lower efficiency [31]. In literature, there has been a variety of manuals that have been published to aid designers in the improved cookstove development process. The Aprovecho Research Center has published several guides, foremost being *Design Principles of Wood Burning Cookstoves* [31, 32]. These guides typically focus on how to obtain the greatest level of efficiency and contain very little on how to optimize the designs for user compatibility.

Other authors, such as Kshirsagar and Kalamakar, have classified and categorized the most common improved cookstoves on the market based upon the combustion type, draft, combustion chamber, feed type and the presence of a chimney [3]. The most popular type of improved cookstove distributed today is the rocket stove [3]. These fairly simple stoves can be made of metal, ceramic, or a combination of both, and are usually portable. Gasifier stoves represent another class of advanced improved cookstoves. These stoves rely on a two stage combustion process to improve the efficiency of the stove. Most rocket and gasifier stoves rely on a natural draft but a few stoves on the market are of the forced draft type and use a small fan to force additional air into the combustion chamber [17]. At times these fans are powered with a thermoelectric generator which has been another area of recent cookstove research [33, 34].

2.3 Poor Adoption of Improved Cookstoves

Despite the health and fuel saving benefits associated with improved cookstoves, they have been adopted at surprisingly low rates. Authors report many reasons for these low adoption rates, ranging from community social factors to how the cookstoves were distributed. [9, 10, 35–38].

In the more recent past, numerous authors have started to recognize and emphasize one particular reason for low adoption rates of past improved cookstoves: the end user needs were not sufficiently considered in the design of the improved cookstoves [11, 12, 17–21]. As Urmee and Gyamfi put it, "many of the past biomass cookstove programs have failed due to a lack of proper understanding of the needs of the people who use this technology" [5].

Literature contains many case studies that illustrate how improved cookstove design was not compatible with the user needs. For instance, a 2001 World Bank survey found that in rural India, many beneficiaries received a two pot model with a chimney, however, many of the users often did not have a use for the second pot so heat was wasted through the 2nd pot opening [27]. Other common examples of improved cookstove flaws include: not being able to burn local fuels [14, 21], stoves being ineffective in heating the surroundings [3, 6, 14], not cooking quickly enough [39–41] , and being incompatible with local cooking equipment [42].

It is evident from the examples that exist in literature that proper improved cookstove selection involves much more than just good performance, it also requires taking into account "a wide variety of cooking practices, cuisines, fuel types, markets, and cultures" [35]. In addition to these factors, another major barrier to wide spread adoption is the high relative cost of improved cookstoves as users usually have very little savings on hand [43]. In one study in sub-Saharan Africa, users were only willing to pay 10 USD for the most preferred improved cookstove [40]. As a result, many improved cookstoves must be donated or sold at a subsidized price [20].

2.4 Background to Usability in the Context of Improved Cookstoves

For the purposes of this thesis, we refer to ISO 9241-11 for the definition of usability; *the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use [44].* The usability of an improved cookstove is more than an evaluation of whether the cookstove can perform certain functions; it is an assessment of how well the cookstove can execute cooking tasks according to the user's expectations.

The usability of a cookstove is influenced by a variety of cookstove characteristics. For instance, how quickly the stove heats up and how quickly food is cooked are two items that are frequently important to end users [3,39,41,42]. How easily the fire can be tended, the types of fuels the stove can burn, and whether users are required to cut wood into small pieces are examples of other characteristics [14, 21, 45, 46]. Additionally, the usability of a cookstove is heavily impacted by how compatible the stove is with local cookware, including the size, number, and shapes of pots [42], as well the stove's ability to cook larger meals [39, 47]. All of these characteristics, plus others, combine to influence how users perceive the usability of a cookstove.

The usability of a particular improved cookstove is also related to how closely it mimics or exceeds the form, function, and performance of the traditional stove it is replacing [5, 11, 18, 38]. Because users have been cooking on their traditional cookstoves for generations, and are accustomed to its nature, it becomes difficult for users to want to adapt their current cooking style to the demands of the new improved cookstove. As Honkalaskar et al. put it, "an improved cooking method that is different from existing practices has less appeal wherever the people using traditional cookstoves are bound to follow the existing practices because of economic, social and religious constraints" [48]. Thus, many improved cookstoves take a secondary role to the traditional stove in the home [36], and are only employed when an extra burner is needed or when the simplicity of the meal being prepared compels its use.

2.4.1 Usability Challenges

There are several challenges that designers face in optimizing the usability of improved cookstoves. First, there is currently no standard way to immediately measure the usability of an improved cookstove as there is in other disciplines [49–51] – thus it is difficult to compare alternative design options. The only robust way of currently measuring the usability of a cookstove is to measure the long term adoption rates of the cookstove. Second, the usability of an improved cookstove is dependent on who is using it and under what circumstances. Therefore, a stove that is highly usable for one user, may not be found usable for another. And third, because improved usability is often at conflict with improved efficiency and emissions, which also happens to be easily quantifiable, stakeholders tend to emphasize the importance of efficiency and emissions instead of emphasizing the importance of usability. All these challenges have culminated such that designing cookstoves for optimal technical performance is much easier than optimal usability.

2.4.2 Benefits of a Usability Focused Design

Despite the associated trade-offs and difficulties that result from increasing the usability of improved cookstoves, there are various potential benefits. The foremost of these benefits being the greater capacity of a highly usable, but marginally improved cookstove to reduce indoor air pollution and fuel use compared to a partially usable, high performing cookstove. This is because the overall impact of improved cookstoves is dependent on high adoption and usage rates. Additionally, cookstove designs that are optimized for usability may help to reverse some of the negative perceptions customers have towards improved cookstoves due to unfavorable previous experiences. Lastly, a few studies [52, 53] have illustrated that users have a difficult time adopting radically different technologies. Thus, improved cookstoves that mimic the usability of traditional stoves, and are therefore more familiar to users, may serve as transitional devices towards cleaner forms of cooking technology.

CHAPTER 3. A GLOBAL REVIEW OF END USER NEEDS

In the past, governments, health organizations, cookstove engineers, and the accompanying literature have done an excellent job at emphasizing a few of the end user needs that should be considered with improved cookstove design– such as the need for cookstoves to burn cleaner and to be more efficient [54–56]. However, these are not the only needs that are important to the end user, and they may not be important at all. User needs such as the ease of use, ergonomic design, cost, and aesthetic appeal of the cookstove are just a few examples of other characteristics that are significant to the customers. Unfortunately, cookstove literature lacks sufficient emphasis about these types of needs.

In literature, there are a few authors who have begun researching these less prominent user needs, but their analysis is usually concerned with only one requirement at a time. For instance, Johnson et al. provided a detailed study about the importance of making improved cookstoves safer [57]. Other authors have brought attention to the need for improved cookstoves to heat the interior of homes [3, 6, 14]. Such examples and research remains scattered throughout literature and it is difficult for readers to become acquainted with the large diversity that exists with end user needs.

Therefore, in this chapter a succinct list is provided of the most common end user needs that should be considered in improved cookstove design. This list was generated through a combination of reviewing hundreds of articles and pulling from our own experiences in the field. Although several of the listed user needs may seem self-evident, displaying them alongside other less-apparent needs is necessary in illustrating the large diversity and the accompanying difficulty that is associated with managing the trade-offs among them during cookstove design. This list is broken into two categories; global needs, and local needs.

3.1 Global End User Needs

The first category is global end user needs. These needs are those cookstove characteristics that were found to be desirable to at least some degree by a large percentage of all people and places. However, because each region and each customer is different, we make no claim that any of these needs are more important than others.

3.1.1 Saves Fuel

Fuel savings are desirable in all regions of the world regardless of environment or cooking practices. Cookstove authors state that the reduction of fuel is perhaps the most compelling reason for consumers to initially adopt an improved cookstove [58]. A study in Bangladesh revealed that 47% of households rate the reduction of fuel costs as the most valuable trait in an improved cookstove [9]. In a paper for the International Conference for Renewable Energies, Karezeki [59] illustrates how in Kenya, improved stoves can save a family 613 USD in yearly charcoal consumption. Economic benefit is not the only motive for saving fuel however, as women also desire the burden of fuel gathering, which can often last up to three or four hours each day, to be lessened [60]. If improved cookstoves were able to reduce the amount of fuel gathering necessary, many women would continue to use the stove long-term [61].

3.1.2 Flexible with Fuel Type

Besides reducing the amount of fuel consumed, users have also expressed the desire to be able to burn a variety of types and sizes of fuel [6, 9]. A common complaint of many improved cookstoves is that the entrance of the stove is too small to insert fuel [14, 21] and the amount of preparation time required to chop the wood into smaller pieces is burdensome [45]. In a recent survey, over 45% of women in a Kenyan village stated that they would not adopt an improved cookstove because it required them to chop the wood into small pieces and it could not burn wet wood [46].

3.1.3 Reduces Emissions

Lessening emissions from cookstoves is imperative for improvements in overall health of people in developing countries and in the effort to decrease global warming. In Guatemala, women spend approximately 5 hours every day near a lit fire [62]. This high exposure contributes to the high number of respiratory diseases contracted from breathing in carcinogens, especially in young children, who are carried on their mother's back for a large portion of the day [63]. Furthermore, in the Biomass Cookstoves Technical Meeting Summary report, the attainment of international emission standards demands 90% emission reductions [64–66].

3.1.4 Cooks Quickly

The inability of an improved stove to cook traditional foods as quickly as the users are accustomed to often impedes the transition from a traditional stove to an improved stove. Such results have been found in rural Africa and Guatemala, where long cooking time was the focus of many user complaints [40, 41]. Contrastingly, in Argentina, improved portable wood cookstoves were reported to cut cooking time in half, which led to very high satisfaction among users [42]. Another complication is that although people want their stove to cook fast, they also want to control the amount of heat in order to cook things at lower temperatures. This control is referred to as the turn-down ratio.

3.1.5 Cooks Local Food

Regions and communities have various customary foods and meals, which the improved stove is expected to cook in a manner equal to or more efficient than the traditional stove [1, 11, 18, 67]. A common misconception is that users will willingly adapt their cooking habits to fit the new stove when, in reality, improved cookstoves should be designed to be compatible with the user's customary cooking practices. Improved cookstoves have frequently failed to meet this need by not being big enough to support and cook large meals [39, 41, 47]. In Chapter 4, more insight will be shared concerning how specific meal types influence the associated cookstove needs.

3.1.6 Accommodates Local Cooking Equipment

Regions where cookstoves are disseminated all employ a specific set of utensils and cooking instruments that the improved cookstove must be compatible with in order to meet their food preparation needs. One such example is the Royal Thai Forestry Department's improved charcoal stove, which is designed with slanted pot rests that can accommodate the local pots that range from 16-32 cm in diameter [68]. This feature permits the user to cook a larger variety of dishes and also accommodates the needs of different sized families in the community. In his 1996 article, Ayoub asserts that, "a fuel-efficient cookstove design requires appropriate information on the shape and size of cooking pots used as well as the cooking practices of the specific region for which the cookstoves are intended" [42].

3.1.7 Easily Maintained

One of the common complaints from improved cookstove users is their dislike for the heavy maintenance required to keep their stoves operational [45, 69]. Often times, recipients of these improved cookstoves choose not to perform the regular maintenance and the stove's efficiency and performance suffers, which contributes to the users abandonment of the improved cookstove. In one Himalayan state of India for instance, stove owners neglected to clean the flu pipe which led to the choking of smoke and back fire [21]. A study of the Patsari Stove Project found that when follow-up stove inspections were provided to assess problems with stove maintenance and other difficulties, long-term adoption rates increased 50% - 85% [16]. Furthermore, a follow up survey performed by the National Council of Applied Economic Research found that in rural India, 71.8% of the improved chulhas installed between 1990-1993 were still fully safe and functional [70]. This was a result of regular reparations performed on the improved stoves by the users during important festivals or family functions.

3.1.8 Able to be Left Unattended

In a recent review of cookstove efforts over the past forty years, it was found that one of the main drawbacks to existing improved cookstoves is that they cannot be left unattended for long periods of time [64]. In developing countries, regular meals can take upward to three hours to cook at a time. The long duration of cooking time needed for traditional meals necessitates the ability to leave the cookstove unattended during the cooking process. A survey performed in rural Africa found that participants preferred the Stovetec stove over the Ugastove because it required less tending along with other factors [40]. Similarly, in Kenya, a survey reported that over 65% of the women would not adopt a stove which required constant tending [46].

3.1.9 Aesthetically Pleasing

The aesthetic appeal of an improved cookstove is an important motivation for many households to purchase improved cookstoves [71]. A study of the Patsari Stove Project found that while only half of stove adopters cited fuel savings as an important factor in keeping the improved stove, most of the users considered the aesthetics of the stove to also be important [16]. In a Kenya study, over 40% of the participants listed a modern appearance of the stove as one of the incentives for adopting an improved stove [46].

3.1.10 Affordable

Though average incomes and monetary systems vary across regions, the price of the improved cookstove, if not affordable for the average user, will impede users from purchasing the stove. In Tanzania, three improved stoves, the StoveTec, the Advent, and the Envirofit stoves were tested. The retail price for the StoveTec and Advent stoves was between 17-24 USD and the Envirofit cost 35 USD. However, most users were willing to pay only 10 USD for most of the improved stoves despite the fuel wood savings, shortened cooking time and pot size compatibility [40]. Literature on improved cookstoves report that most improved cookstove programs provide the cookstoves at little to no cost. However, some authors believe that large discounts by themselves are unlikely to promote substantial adoption and should be avoided [9].

3.1.11 Safe

Safety is a desirable and necessary trait of improved cookstoves [6]. Several areas of safety to be concerned about are tipping, containment of flaming embers if tipped over, surface temperature, heat transmission to surroundings, and cookstove handle temperature [57]. Burns, scalds and cuts are the most common safety concerns that result from stoves with improper safety precautions [57].

3.2 Local End User Needs

Despite the general applicability of the user needs outlined in the previous section, we found there exists a set of end user needs that are unique to only certain regions or certain circumstances. In the next portion of this chapter it will be outlined what these needs are and when they might be applicable. Though not an exhaustive list, the following examples are those needs that most regularly appear in published literature.

3.2.1 Provides Space Heating

One of the most common additional uses of traditional cookstoves is using it as a heat source in colder climates [6, 14, 64]. In central India, for example, where temperatures reach as low as 2 degrees Celsius during the winter, cookstoves serve as the primary heat source in the home [72]. Several improved cookstove programs have suffered low adoption rates because the improved stove could not perform this additional task [14]. However, intentionally providing space heating is often at competing terms with other cookstoves objectives, such as stove efficiency, since it removes heat from the combustion process.

3.2.2 Heats Water

The ability to quickly and conveniently heat water is another end user need that differs in extent between regions [64]. For instance, in a small African village, it was found that 27.4% of the wood energy was used for heating water [13], while in a Himalayan region, only 8% of the wood energy was used for heating water [21]. Heated water is predominately used for both meal preparation and for bath water [11, 18].In some regions, the cookstove's ability to heat water is so indispensable, that a pot used for heating water is permanently attached to the stove. [73]. The Aprovecho Research Center has proposed benchmarks of improved stove performance for heating of water with wood-burning improved cookstoves, which have been adopted by numerous international organizations [74].

3.2.3 Repels Insects

In some regions, the smoke from cookstoves is desired for the purpose of repelling insects or fumigating thatched roofs [42,60]. This desired characteristic poses potential conflict to the goal of reducing indoor air pollution. Most families in developing countries cannot afford refrigerators, so smoking food is necessary for food preservation, and keeping insects and rodents away [75]. Furthermore, many regions are plagued by disease-carrying mosquitoes and poisonous insects, which are most effectively dispelled from the user's homes using smoke from the cookstove [76]. Additionally, cookstove designers find that although cleaner improved cookstoves may result in a decrease in asthma rates by reducing indoor air pollution, they may trade this benefit for an increase in malaria rates since the mosquitoes are no longer being smoked out of the house [75].

3.2.4 Portable

The ability of a cookstove to be portable is also a regional preference and highly dependent on traditional methods of cooking. The portability of a cookstove has been reported in places such as Mali, Kenya, Chad, and many other locations [13, 42, 77]. In regions where large seasonal temperature variations exist, the ability to cook indoors and outdoors is often desired [78].

3.2.5 Provides Light

Stoves frequently serve an additional non-cooking purpose of producing light to the interior of a home [41]. Kshirsagar and Kalamkar reported that one of the largest obstacles to the acceptance of clean stoves is they do not live give off light like traditional cookstoves [64]. The perceived value of this additional feature is often dependent on the availability of other fuel sources in the community. Kerosene lights or battery powered LED lights are a couple of the alternative light sources that provide light and may lessen users dependence on an open fire or cookstove for lighting. Using a thermoelectric generator in conjunction with a cookstove is another method proposed by Champier to produce light [33].

3.3 Concluding Remarks from Chapter 3

There exists among cookstove users a very diverse set of needs and expectations regarding how an improved cookstove should function. Some of these needs are fairly universal, while others are conditional to the specific circumstances. The purpose of this chapter was to educate engineers and designers that end users care about much more than just efficiency and smoke reduction–they want a product that helps them achieve their cooking goals with effectiveness, efficiency and satisfaction.

CHAPTER 4. REGIONAL, COMMUNITY, AND HOUSEHOLD FACTORS THAT DETERMINE END USER NEEDS

In chapter 3 we introduced the idea that cookstove users have more diverse needs than just the desire for reduced smoke and improved efficiency. For instance, users desire cookstoves that can burn fuel from local sources. Satisfying this need, however, is complex due to these fuel sources differing depending on what community a user lives in, the time of day, or what the current season is. Thus we see that assuming a group of users all have a homogeneous set of needs is incorrect.

Literature has stated repeatedly that prior to cookstove design, a study of the user's needs and culinary practices must be accomplished [64]. However, very few authors have gone to the extent to provide guidance to readers on how these user needs and culinary practices will vary among the users. This chapter aims to provide some of that instruction by identifying the various regional, community, and household factors that in large measure determine the user's needs. Figure 4.1 contains a visual summary of these factors.

4.1 Regional Factors that Affect Cookstove Use

Simon [19] reports that the delivery of suitable household cooking technologies must account for the diverse regional needs that exist. Meaning, a community that lives in one region may have completely different needs than a community living in a different region, regardless of geographical distance. This realization may seem fairly self evident, but in general there is a lack of depth regarding the implications of this reality.

4.1.1 Food Type

Possibly the most significant factor that varies between different regions is the type of local food that is prepared using a cookstove. Each region will have its own unique dishes and methods

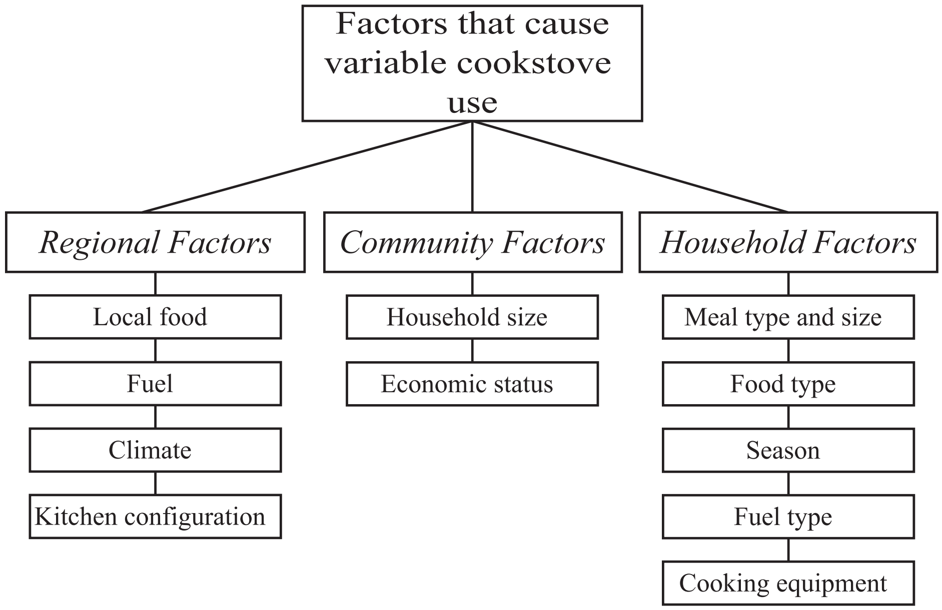


Figure 4.1: Visual depiction of the different factors that affect cookstove use.

for cooking meals [1, 58, 61]. In the previous chapter we established how the ability to cook local foods is a primary user need, in this section we attempt to show how different types of food might affect cookstove use. Cookstove variables that are influenced by the type of food being cooked include cooking time, heat, number of required burners, and required cooking surface type. Table 4.1 lists the most common food dishes for three different regions and illustrates how these dishes affect the expected function of the improved cookstove.

Table 4.1: Examples of how different regional foods affect the use of cookstoves

Place	Local Food Dish	Functional Considerations
Mexico	Tortillas	High heat for a short amount of time and a large flat cooking surface required
Bangladesh	Curry	Low simmering heat that can be sustained for long periods of time and can hold large pots
Kenya	Ugali	Boil large pots of water and support viscous stirring of thick dough like substance

4.1.2 Fuel Type

The type of biomass fuel that is used differs between regions and depends on the resources that are available. For instance, agricultural based regions often use crop residues, such as rice husks [79], corncobs [80], or jatropha plants [81] as fuels. Many African cookstove users prefer to use charcoal when funds are available [12]. Whereas, regions with higher elevation often rely heavily on animal dung to supplement their fuel sources. Thus, the type of fuel that is most frequently used in a region, can vary substantially from region to region.

4.1.3 Climate

The difference of climates between regions will result in varying cooking methods and non-uniform cookstove performance. For instance, the climate often determines what additional functions the cookstove must perform, such as in snow bound regions, where cookstoves are frequently used for space heating [21]. Climate also influences the location of where cooking takes place. In regions where the weather may be favorable, cooking often occurs outside [39], which eliminates the need for chimneys. Climate can also affect the durability of stoves and what type of construction materials are acceptable. In one coastal region, rapid corrosion of metallic cookstove parts occurred causing premature failure [19]. Precipitation in the region is another factor that must be considered, as this affects the moisture content in the wood [82]. Furthermore, prevailing wind patterns can influence the type and placement of chimneys [19].

4.1.4 Kitchen Configuration

Another factor that influences the varying use of a cookstove between regions, is the location and size of the kitchen. Numerous authors have reported that kitchens can be located either inside the main house, outside, in a separate shelter designated for cooking [14], or any combination of these. For those homes in which the kitchen is located indoors, L'Orange discovered a dramatic difference in the kitchen size and the air exchange rate across 13 different countries [83]. These varying kitchen configurations should be considered when determining the acceptable size of the stove, the need for a chimney, safety implications, and the preferred position of the stove in relation to the cook.

4.1.5 Summary of Regional Factors

In this section, we presented four regional factors that should be considered when designing a cookstove. These four factors are likely to vary between different regions and cause inconsistent use and performance of cookstoves. Table 4.2 summarizes these regional factors by giving examples from four different regions and how each region has its own unique design considerations. From this table, it is clear that a cookstove that is to function in different regions should be able to accommodate a wide variety of uses.

Table 4.2: Table showing how different regional factors affect the use of improved cookstoves and that no two regions are alike

Region	**Climate**	**Fuel Type**	**Food Type**	**Cooking Location**	**Cookstove Considerations**
Andes Region, Peru	Cold winters and mild summers, windy, high elevations	Agricultural waste, dung, and some wood	Corn, potatoes, and guinea pigs	Indoors	Space heating, vent smoke, diverse fuel types, main cooking utensil is a pot
Michoacan, Mexico	Moderate temperatures with cooler winters, heavy rains in June	Pine, oak, brush	Tortillas, nixtimal, tamales, beans, and rice	Mostly indoors	Small amount of space heating, vent smoke, large stove opening, flat cooking surface, pot for heating water
Embu, Kenya	Generally warm with occasional cool, heavy rains from March to June	Wood and Charcoal	Ugali, githeri, sukuma wiki	Mostly outdoors	High intensity heat for boiling and low heat for simmering, aluminum sauce pan, portability is desired
Sylhet district, Bangladesh	Warm with heavy rains during summer	Wood, twigs, leaves, and cow dung	Rice, fish, pulse, vegetables and chicken	Inside during rainy season	Portability, large opening for leafy type fuel, most food is boiled in round bottom pots, at least two burners, long cooking times

4.2 Community Factors that Affect Cookstove Use

Just as the use and performance of a cookstove will vary between different regions, it will also differ between households in the same community. As illustration, consider the different adoption percentages that are cited in literature, ranging anywhere from 5% [21] to 90% [84]. These adoption percentages indicate that only a portion of the community is satisfied with the improved cookstove, whereas the remaining portion of the community finds the stove's performance of functionality insufficient. The question then arises of why certain households find the improved cookstoves satisfactory and others do not. In this section we partially explore the answer to this question by listing two of the most significant factors and differences in a community that lead to varying use of improved cookstoves.

4.2.1 Household Size

The number of people living in a household has a significant impact on the type of cookstove and how it is used. Several studies have documented how household size ranges within a community, such as in one Kenya community, household size ranged from one to eighteen people [85]. In another study, household size of a Bangladesh community ranged from two to eleven people [86]. Varying household sizes require different types and amounts of food, different stove sizes, different cooking utensils, and the different fuel types.

4.2.2 Economic Status

The economic status of a family can have a drastic effect on what type of stove they purchase, what type of fuel they use, and the type of food they cook. In a study of Mexican households, it was found that the poorer class of people relied on shrubs more often for fuel than the wealthier class who relied exclusively on pine and oak wood [82]. Additionally, several researchers have found that those of a higher economic standing are more likely to adopt improved cookstoves [10]. To better improve widespread adoption, cookstove design should consider the differing needs of all economic levels.

4.3 Household Factors that Affect Cookstove Use

The third type of factor that influences the fluctuating use of cookstoves, and possibly the most overlooked in literature, is the continually changing circumstances and cooking practices within a single household. Currently, it is common for a household to employ the use of several cookstoves, each cookstove having their preferred function or role, to meet these changing circumstances. Additionally, Muneer found that a single set of preferences within a household cannot be assumed [12]. In this section we explore the factors that lead to such diverse cookstove use within a single household.

4.3.1 Meal Type and Size

The size of meal being cooked is inconsistent and heavily influenced by two factors, household size and what type of meal is being cooked. For instance, breakfast is a much smaller meal than lunch in many cultures and subsequently requires less firepower and fewer cooking surfaces. Johnson [78] found that meal size could range anywhere from 1.2 to 24.7 kg in an African village and similar results could be expected elsewhere in the world. Successful cookstoves must be able to accommodate these varying meal types and sizes.

4.3.2 Food Type

In previous sections, we established the primary need that cookstoves must be able to cook local foods and that food type will vary from region to region. We also want to establish that food type will vary within a household from meal to meal, day by day, and from season to season. One study in Kenya found there exists six different staple food types that people commonly cook [46]. This means a wide range of cooking times, firepowers and other cooking parameters are employed within a single home.

4.3.3 Season

The changing of seasons contributes to fluctuating use of cookstoves. For instance, during the winter cookstoves are often used for space heating, but this feature becomes undesirable during the summer months. The changing of seasons also motivates the use of seasonal fuels. In Bangladesh and Peru, for example, leafy matter and other agricultural residues are burned during the dry season, whereas during the wet season, wood becomes the primary fuel type [87, 88]. Cooking location also fluctuates with the changing of seasons. Outdoor cooking is more common during the dry months and throughout the planting and harvesting seasons so that meals can be served closer to the fields [13]. Season also affects the type of food that is prepared and consumed. From these examples, it becomes clear that if a single cookstove is to provide for the household cooking needs, it must be able to adapt with the changing of seasons.

4.3.4 Fuel Type

The type of fuel used in a household fluctuates with the changing of season, the meal being cooked and how quickly the meal needs to be prepared. It also depends on the availability of local fuel supplies and the user's finances [12]. In Kenya, for instance, women prefer to cook with charcoal when they can afford it or when the weather is bad, otherwise, they use less expensive biomass fuels [89].

4.3.5 Cooking Equipment

As explained earlier in this chapter, improved cookstoves need to accommodate local cooking equipment (pots, pans, skillets, etc.). In this section we want to emphasize that the type and size of equipment will also vary depending on the size of the meal and the type of food being prepared [42, 62, 67, 68, 73]. For instance, in one study in Uganda, participants overwhelmingly preferred the StoveTec stove compared to other models because its removable pot skirt could accommodate the variety of cooking pot sizes they cooked with [40].

4.3.6 Summary of Household Factors

In this section we explained a variety of factors and practices that cause cookstove use to fluctuate on a daily, seasonal, and meal to meal basis, all within the same household. These factors help explain why so many improved cookstove owners employ multiple cookstoves to meet their cooking tasks. To further help show how a single household has fluctuating needs and expectations of their cookstove, we have included Table 4.3 that exhibits our findings.

Table 4.3: Examples of different scenarios in a single household that affect the use of improved cookstoves.

Scenario	Food Dish	Season	Fuel Type	Cooking Equipment	Cookstove Considerations
A	Beans	Summer/ wet	Damp pine	Large pot	Large pot required to cook several day supply of beans, long cook time at low simmering heat, damp wood is difficult to light, large opening in stove needed to insert wood
B	Tortillas	Winter	Pine or oak wood	Comal	Large flat comal used to cook tortillas at high heat, large opening to stove needed, stove heats as heat source
C	Nixtimal	Summer	Mixture of pine, leaves, and agricultural waste	Large pot	large pot used to mix nixtimal, long cook time, requires constant tending since leafy fuel is consumed quickly

4.4 Summary of Chapter 4

In this chapter, the environmental and social factors were outlined that contribute to the diverse and varying uses of cookstoves. End user needs can vary drastically between different regions, within a community, and even vary within the walls of the same home. Engineers and designers need to be cognitive of these factors to ensure that cookstoves appeal to the largest customer base as possible.

CHAPTER 5. TAILORED DESIGN METHODOLOGY

The findings displayed in the previous chapters of this thesis reveal that designing improved cookstoves that are functionally, culturally, and technically acceptable is a difficult objective. Due to the complex nature of the design problem, it is important that engineers and designers of improved cookstoves apply design methodologies that focus on the needs of the customer. Design literature already contains many such published methodologies that emphasize the importance of discovering and using customer needs throughout all stages of development [90–92].

However, these methodologies assume that a sufficient sample of end users is reasonably accessible to the design team – an assumption that does not often hold true when designing for the developing world. Existing methods also assume that the design team is capable of accurately interpreting customer statements and other contextual information. Such capabilities often require an understanding of the user's culture and language. Unfortunately few engineers are trained in this area.

These challenges are even further complicated by a variety of barriers that hinder research team's efforts to focus on customer needs. These three barriers include (but are not limited to):

1. Physical Distance Design teams are often unable to apply better design methodologies since these methods rely on extensive interaction with the customers. When design teams and end users are separated by physical distance, as is often the case for cookstove design, these types of personal can be very time consuming, costly, and therefore do not occur as often as they should.

2. Cultural Difference Because of limited interaction with the customers, design teams often have a difficult time understanding or appreciating the culture, behaviors, and daily obstacles of those who use improved cookstoves. When faced with this problem engineers tend to make simplifying assumptions to formulate a solvable problem. Unfortunately engineers of-

ten over-simplify the cooking needs of the end user and develop a false belief that any cleaner burning, more efficient cookstove will be preferred over current traditional cookstoves.

3. Stakeholder Imbalance Heavy emphasis placed on improving cookstove efficiency and reducing harmful emissions in the literature, media, and funding organizations has caused many design teams to under-appreciate other critical cookstove characteristics that are essential to the customer. This imbalance in stakeholder emphasis has resulted in many efficient and low emission cookstoves that go unadopted because they don't meet the end user needs.

While the method presented in this chapter does not remove these barriers, it does provide a way for the design team to minimize the effects that can occur because of them. Specifically, this chapter presents a design methodology that (i) emphasizes the extraction of global and local market requirements for the cookstove market, (ii) shows how those market requirements can be systematically translated into cookstove performance requirements that the design team can work towards, and (iii) emphasizes that the design team should validate proposed designs by frequently evaluating the market requirements.

This design methodology differs from other cookstove design methodologies in that its focus is primarily on the early stages of the development process. Several authors have published design processes to assist with the technical and detailed design aspects of cookstove development [3, 31, 93, 94] but these methodologies require the design team to have already identified the requisite customer needs. Our experience has shown this can often be just as difficult as designing the actual cookstove, and decisions made during early stages will have a profound impact on design efforts during later stages. Therefore, the significance of determining the appropriate user needs, necessitates a detailed description of the initial stages of cookstove development.

The method presented in this chapter is derived from what we have observed in literature and from our own experience developing products for the developing world. The format of this chapter will follow the five steps of the proposed methodology as shown in Figure 5.1. For each step, a brief discussion will be given of how these three barriers have negatively impacted improved cookstoves in the past, and how to overcome these barriers in future design efforts.

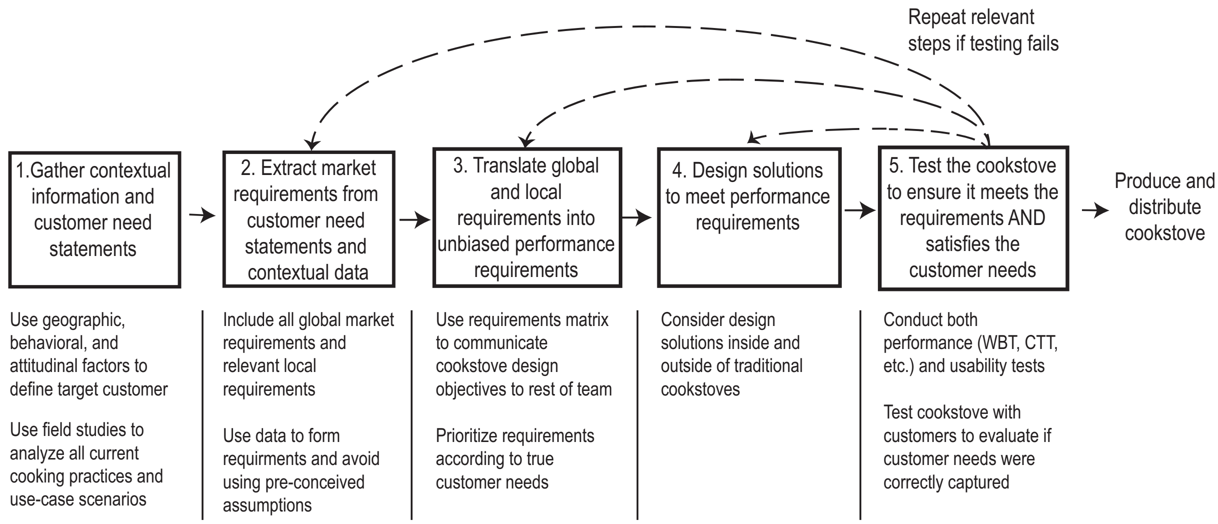


Figure 5.1: A simple five step diagram of the proposed improved cookstove design methodology

5.1 Step 1: Gather Contextual Information and Customer Need Statements

In the first step of this proposed methodology, the objective is to gather contextual information and details about the customer's needs in order to make future design decisions. The importance of this first step has been emphasized by numerous authors [13, 21, 39, 48], but it "has generally been limited to passive inputs in late phases of the product development process" [95]. The quality and quantity of information gathered in this step will determine the outcomes of later stages of development.

In a developing world setting, gathering meaningful data and information is perhaps the greatest challenge in designing a new product. There is often little existing data and field travel, communication and obtaining large sample sizes is costly and inefficient. Cookstove designers must approach this step with an open mind and avoid only seeking the data that validates their initial assumptions or hypotheses. To aid in overcoming these challenges we recommend the following two suggestions.

5.1.1 Identify the target consumer market

Initially, designers must identify and define their target consumer market. The more detailed the description of the target market is, the more focused the cookstove design can be on the customer needs. In a developing world setting, geographical boundaries are often used to define the target market, but it is unlikely that everyone living within those boundaries will be target customers for that improved cookstove. Thus, the target market should be more explicitly defined in terms of demographic factors, such as family size, economic status, main food types, and primary fuels used. Attitudinal segmentation may also be beneficial, such as identifying the beliefs, values, and perspectives that further uniquely define the customer. In some cases, it may be difficult to define the target market in the developing world without information obtained from initial field studies. In such cases, the market description should be continually refined as more knowledge is obtained about the target customer and segment.

5.1.2 Perform Field Studies to Gather Data and Customer Need Statements

A wide assortment of data needs to be collected at the beginning of a new cookstove project. Examples of required data include family sizes, the type and number of pots and pans used, the types and amount of fuel used, location of main cooking activities, the type and volume of food most commonly prepared, and the time required to cook traditional foods. The following references contain examples of field studies that collect such data [13, 21, 40]. It is also beneficial to gather other large scale contextual data, such as GDP (Gross Domestic Product), life expectancy, hospital visits, deforestation problems, etc.

The primary mechanisms currently used for gathering customer statements with improved cookstove projects are interviews, focus groups, and observing existing cookstoves in use. When surveying potential users, two common methods used to determine preference are the "willingness to pay" methodology as well as the "stated preference survey technique" [96]. Adkins et al. also attempted to determine customer preference by having local residents test a variety of existing cookstove models and then asking what features they preferred [40]. However, caution should be exercised with this method since a community's willingness to give feedback is often tied heavily to their culture.

While gathering data, it is very important to realize that a single cookstove user will employ a wide array of cooking techniques and practices. For instance, the type of fuel used can vary between the summer and the winter, or the user's cooking methods for preparing breakfast may be different when compared to lunch preparation. Researchers working in the developing world should engage in data collection methods that will capture the whole spectrum of cookstove use, even if field studies are only for a short period of time.

5.1.3 Summary of Step 1

Upon completion of this step, researchers will have accumulated a wide assortment of measurements, observations and statements from the potential cookstove customers, as well as a variety of other contextual data. Together, these sources of information will be prove to be critical throughout the design process by providing the foundation for design decisions in the later steps.

5.2 Step 2: Extract Market Requirements from Customer Need Statements and Contextual Data

The second step of the proposed design methodology is to extract the market requirements from the customer need statements and contextual data collected in the previous step. Market requirements define what type of cookstove functionality is required in order to satisfy the customer needs. For example, a customer during interviews might say something like, ”I wish it didn't take so long to cook my meals,” which would translate into a market requirement of, ”The cookstove cooks quickly”. Readers at first may not realize the subtle difference between customer needs and cookstove requirements, but it is valuable to take the time to understand.

In the past, governments, health organizations, cookstove engineers, and the accompanying literature have done an excellent job in emphasizing a few of the market requirements, such as the need for cookstoves to burn cleaner and to be more efficient. However, these are not the only requirements that are important to the customers, and they may not be important at all in some cases. Requirements such as the ease of use, ergonomic design, cost, and aesthetic appeal of the cookstove are just a few examples of other characteristics that are significant to the customers. Unfortunately, cookstove literature lacks emphasis on these types of requirements.

Chapter 3 of this thesis contained a large list of customer needs that are common throughout the world. To help illustrate the process of extracting market requirements from customer needs, a summarized list is provided below of how those needs can be translated into market requirements.

5.2.1 Global Market Requirements

- The cookstove saves fuel
- The cookstove improves air quality
- The cookstove is flexible with fuel type
- The cookstove cooks quickly
- The cookstove accommodates local cooking practices
- The cookstove is easily maintained
- The cookstove can be left unattended
- The cookstove is aesthetically pleasing
- The cookstove is affordable
- The cookstove is safe

5.2.2 Local Market Requirements

- The cookstove provides space heating
- The cookstove heats water
- The cookstove fumigates insects
- The cookstove is portable
- The cookstove provides light

5.2.3 Summary of Step 2

In this step of the proposed methodology, the objective is to identify the appropriate market requirements that capture the needs of the end user. There are certain requirements that are applicable to nearly every region (global requirements) and needs that are unique to certain regions or circumstances (local requirements). In this section, we provided a list of the most common requirements as found in literature and from our own experience. From this list it is apparent there is a very diverse set of market requirements that a single improved cookstove may need to satisfy. Each region and customer is unique and a "one-size-fits-all" type of model will not satisfy. Identifying the correct market requirements for the specific target market is fundamental to creating an improved cookstove that is culturally and functionally acceptable.

5.3 Step 3: Translate Global and Local Requirements into Unbiased Performance Requirements

In the previous section we presented a list of the most common market requirements from around the world. Although these market requirements describe end user expectations for how the cookstove is to perform, they do not provide the sufficient detail necessary to design and engineer an improved cookstove. That role is satisfied by translating the customer needs into unbiased performance measures and associated target values, which together form a performance requirement. As Ulrich and Eppinger point out, performance requirements do not describe "*how* to address the customer needs, but they do represent an unambiguous agreement on *what* the team will attempt to achieve in order to satisfy the customer needs" [92]. For instance, if a market requirement is for the cookstove to cook quickly, the corresponding performance requirements might be the rate at which the stove must heat up, or the amount of time required to boil a specified amount of water.

Despite the importance of establishing appropriate performance requirements, it has been difficult for many past improved cookstove programs to do so because of the three barriers outlined in the introduction. For instance, because travel to developing countries is so costly, often only a small portion of the design team is able to experience the true customer experience first hand. As a result, there are apparent disparities between the knowledge captured during field studies, and the performance requirements established by the rest of the design team. Additionally, it is simple for designers to introduce bias into the performance requirements, as they tend to rely on their preconceived first-world notions to determine whether a design is good, instead of making data driven decisions. Lastly, the performance requirements are susceptible to influence from a subset of stakeholders who may emphasize the importance of only a few cookstove characteristics.

The existence of these inherent barriers makes it necessary for design teams to be deliberate in how they go about establishing and using performance requirements. We provide the following guidelines to assist in this process.

First, determine the priority of the different global and local market requirements that were gathered in the previous step. This priority should be governed by customer preference and not by external objectives. Just because something might be more of a global requirement, does not mean it should be given higher priority than a local requirement. Or vice versa. Establishing priority provides insight of what to do when design trade-offs occur.

Second, associated with each market requirement there needs to be an objective set of measures that define whether or not a particular design satisfies the market requirement. Sometimes multiple performance measures will be needed to accomplish this goal. Table 5.1 contains a few examples of different performance measures.

Table 5.1: Examples of market requirements and their associated performance measures

Market Requirement	**Performance Measures**
The cookstove cooks quickly	Time to light fire Time to boil 1 liter of water
The cookstove is safe	Temperature of outside surfaces
The cookstove is affordable	Cost to purchase Cost to maintain per month
The cookstove does not pollute	CO produced CO2 produced Particulate matter emitted

Third, it is important for the design team to document the baseline performance of the traditional cookstove according to all the performance measures set. Once the baseline performance is clearly documented, the design team can then select the appropriate performance targets the new cookstove design should ideally achieve. Typically these values will represent an improvement over the benchmarked performance values, however at times setting a target value lower than that of the benchmarked value may be needed in order to achieve a higher priority performance target.

5.3.1 Organization of the Performance Requirements

Design teams may find it challenging to incorporate the data from the above stated guidelines into the design team's efforts. We recommend the application of some type of structured process/tool to assist in this process. By doing so, the most important customer needs stay at the forefront of the design efforts. We have found that there are a variety of tools that can help facilitate this process, but the one we prefer to use is that of a requirements matrix.

The requirements matrix is a simple and straightforward organizational structure that can be easily adapted to cookstove development. For each global and local market requirement, it links the appropriate performance measures and target values. In Figure 5.2, we provide an example matrix for a cookstove development project we were involved with in Northern Peru. It is worth noting just a few of the ways that this requirements matrix reflects the underlying needs of the customers, as follows:

- Customers in this region repeatedly expressed a desire to be able to use their cookstove on the table tops. Therefore, specific target values were set for the maximum temperature allowed on the underside of the stove as well as the maximum weight; both of which influence the stove's ability to be put on a table.

- Customers in this region routinely cook with both wood and charcoal fuels. Therefore, the associated performance measure and target value specifies that the improved cookstove should cook with both types of fuel.

- Many customers in this region cook large batches of "corn beer" on a weekly basis. This requires very large pots in comparison to other regularly used pots. Therefore the target values for the maximum diameter of acceptable pots was increased to 30 cm.

These are just a few examples of how this requirements matrix was customized to the needs of this particular region. The displayed benchmarked performance values come from testing the

Customer Description: Residents living in the Tambogrande region near Piura, Peru. Target customers live in homes made of brick and estera, and primarily cook with wood and charcoal indoors.

#	Market Requirement	Priority (1-5)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	The cookstove is affordable	1	X	X								X												
2	The cookstove uses locally available fuels	1			X	X										X	X	X	X	X				
3	The cookstove can be placed on any surface	3					X					X												X
4	The cookstove accommodates local cooking practices	3			X			X	X	X														
5	The cookstove is easy to use	2	X								X		X						X	X				X
6	The cookstove is aesthetically pleasing	5		X				X				X												
7	The cookstove cooks quickly	2				X							X	X					X					
8	The cookstove is fuel efficient	4				X									X									
9	The cookstove has low indoor air emissions	3														X	X	X						
10	The cookstove can be left unattended	4				X	X												X	X				
11	The cookstove is safe	4														X	X	X			X	X	X	

#	Performance Measures	Unit of measurement	Baseline Performance	Improved cookstove target performance: Worst acceptable	Best acceptable	Target
1	Cost to operate	Soles/Week	8	10	3	8
2	Cost of cookstove to purchase	Soles*	25	25	10	20
3	Fuel types that cookstove can use	n/a	wood only	wood only	wood & charcoal	upper limit targeted
4	Largest size of fuel that can be inserted (diameter)	cm	6	4	8	6
5	Temperature of underside of stove	Degrees (°C)	54	58	35	50
6	Number of cooking burners	Number of burners	2	1	2	2
7	Largest diameter of pot/pan that can be used	cm	35	25	35	30
8	Smallest diameter of pots/pans that can be used	cm	10	15	10	10
9	Time required to train customer how to use new stove	Minutes	5	5	25	15
10	Asthetic appeal to the customer	n/a	not attractive	stove is somewhat attractive	stove is attractive	upper is targeted
11	Time to light stove	Minutes	30	40	10	15
12	Time to boil 5 liters of water	Minutes	56	60	20	30
13	Modified thermal efficiency	% Efficiency	11	15	35	25
14	CO released during WBT	Grams	30.5	30	18	22
15	CO2 released during WBT	Grams	366	350	250	300
16	Particulate matter released	g/Mj	1E-15	4E+14	1E-13	1E-13
17	Turndown ratio **	n/a	1.2	1	2	1.2
18	Time stove can go unattended	Minutes	15	10	25	15
19	Temperatue of outside surface	Degrees (°C)	50	55	40	50
20	Presence of sharp edges	n/a	no sharp edges or points exist	edges pose medium danger	no sharp edges or points exist	upper limit is targeted
21	Force required to tip burning cookstove	Newtons	40	20	50	30
22	Overall weight of cookstove	Kg	5	12	3	7

*A Sole is a unit of currency in Peru, equivalent to a Pervuvian Nuevo sol.
**The turndown ratio is defined to be the maximum firepower divided by the minimum firepower. It denotes the width of the operational range.

Figure 5.2: Example requirements matrix for the Tabogrande region in Peru

traditional charcoal cookstove in a lab setting and observing its use in the field. Figure 5.3 shows a picture of one such stove. In cases where several traditional stoves are used, it would be appropriate to benchmark all of them. In this example we just include one for simplicity.

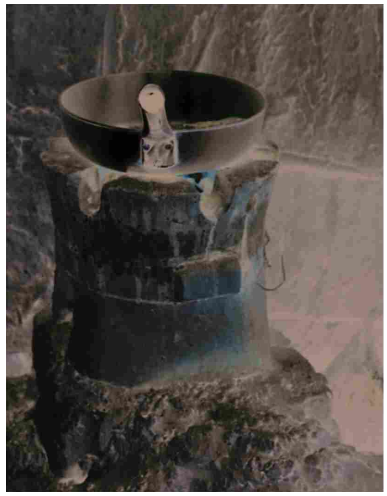


Figure 5.3: Photo of traditional charcoal cookstove used in the Tambogrande region of Peru.

5.3.2 Step 3 Summary

The formation of clear and accurate cookstove performance requirements is requisite for satisfying customer needs. Performance requirements consist of performance measures and associated target values. Performance requirements help turn ambiguous design challenges into a set of concrete objectives that engineers can then work towards.

5.4 Step 4: Design Cookstove to Meet Performance Requirements

Following the successful identification of customer needs, market requirements, and the establishment of appropriate performance requirements, designers will have gathered sufficient data and user requirements to begin designing. The goal of this step is to produce a cooking solution that will achieve the target values established in the previous section, which in turn will satisfy the market requirements.

It is important during this step that designers do not experience cookstove myopia. This term is used to describe a situation in which engineers are so fixated on designing a new cookstove that they fail to consider all possible design alternatives. For instance, it is plausible that in some circumstances users would benefit more from an improved fuel source instead of a new cookstove. Additionally, they might experience greater health benefits by simply ventilating the kitchen, instead of replacing their traditional cookstove. Therefore, this step emphasizes the importance of considering all cooking solutions and not just assuming the answer is a better cookstove.

There are a few examples in literature in which engineers have successfully employed solutions that differ from the conventional improved cookstoves. In rural Mumbai, researchers placed a twisted tape device into the combustion chamber of the traditional stove and significantly reduced the amount of fuel required by 21% [48]. In northern Peru, researchers incorporated pot skirts with the traditional cookstove to improve the overall thermal efficiency by 36% [23].

Due to the nature of the multi-objective design space, optimization and other proven methods should be employed to converge on the best design solutions [97, 98]. We will refrain from listing all possible design activities in this step, but encourage designers to include best practices of idea generation, concept selection, modeling, and prototyping.

5.5 Step 5: Test the Cookstove to Ensure it Meets the Requirements and Satisfies the Customer Needs

A critical step that must be included in every design process is the frequent testing of cookstove designs in both the lab and with the intended users in the field. In general, testing cookstoves intended for the developing world is much more difficult than testing a new product intended for the developed world. It is expensive to travel and test cookstoves with actual users, and it is challenging to simulate actual cooking conditions in a lab setting [3, 99–101]. Due to these barriers, cookstove testing has often been reserved for later stages of development which inherently increases the risk that the design will not meet the end user's needs.

There are two purposes for testing cookstoves. First, to ensure that the performance of the cookstove meets or exceeds the target values. And second, to validate that the performance and market requirements identified earlier are actually representative of what the customers in the target population desire. For instance, during initial field studies, the customers may express that reducing the amount of fuel burned is a high priority, but after testing the proposed improved cookstove design with actual customers, it may become apparent that the ease of lighting and stoking the fire is more important to them than saving fuel. These types of discrepancies can occur not only due to the incorrect identification of the customer needs, but also from the customers not

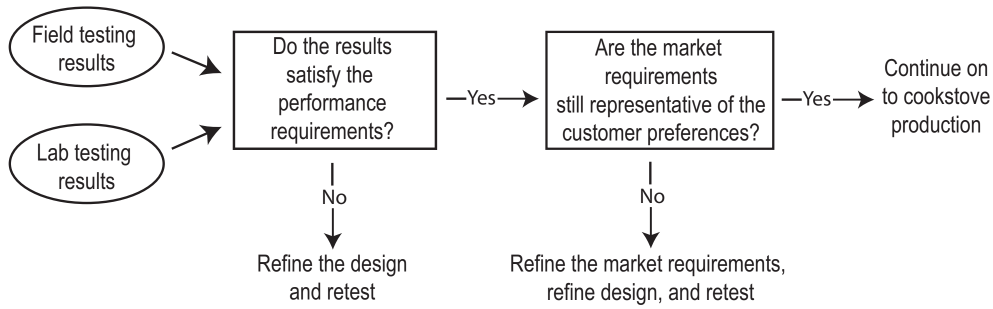


Figure 5.4: How to incorporate cookstove testing throughout the design process

knowing what they prefer until they are given the chance to experience the improved cookstove firsthand. Figure 5.4 provides a summary of this process.

A relatively encouraging example of cookstove testing and iteration occurred with the design and dissemination of the Patsari improved cookstove in rural Mexico. Instead of distributing the entire quantity of improved cookstoves at one time, organizers distributed them in three different stages. Between each subsequent stage, improvements were made based upon results of the previous stage. As a result, recipients of the stove in the third stage reported being much more satisfied with their cookstove than those of the first stage [20].

5.6 Chapter Summary: Tailored Design Methodology

The complexity of designing improved cookstoves that satisfy a diverse customer base is significant. Clearly, following a systematic design process can help manage that complexity but unfortunately efforts to apply structured design processes are often thwarted by three specific barriers: geographical distance, cultural differences, and a stakeholder imbalance. As a result, there is a need for further guidance in literature about how to adapt the design process (particularly during early stages of development) to minimize the negative effects of these barriers.

This chapter has presented a five step methodology that helps identify, extract, and then apply the customer needs in such a way that design teams, regardless of their experience with the customer's foreign culture, can successfully focus their energy and priorities on developing cookstoves that are user centered. To assist in focusing efforts on pertinent customer needs, this chapter provided a list of the most common customer needs from around the world as found in literature and from our own experience. Interestingly, this chapter shows that there are needs that are both global and local in scope, and designers should expect significant variation in local needs among different customer segments.

An additional outcome of this research is that a customer focused approach encourages design teams to examine a broader set of design solutions than would normally be considered. Instead of just designing better improved cookstoves, design teams are developing cooking solutions that solve customer problems, which may or may not result in an improved cookstove.

CHAPTER 6. CASE STUDY: A USER CENTERED COOKSTOVE FOR TAMBOGRANDE, PERU

In order to test our hypothesis that greater impact can be achieved when cookstoves are optimized for usability, we engaged in a year-long experiment. This experiment entailed designing and testing a cooking device for residents living in rural northern Peru specifically focusing on what effect and impact a cooking device optimized for usability would have. Though our approach is primarily experimental in nature, the methodologies used partially pull from the case study method as proposed by R. K. Yin [102]. In particular, the process of collecting and analyzing data using multiple data points and adapting the research based upon initial findings.

6.1 Usability Field Experiment: Tambogrande, Peru

The Tambogrande district is a collection of small communities located in northwestern Peru. Despite approximately 70% of the homes in this rural area having electricity [103], a significant portion of the rural population use open flame biomass cookstoves for their primary cooking duties, and only 15% of those households have a chimney [104]. Over 8 million people in total in Peru are effected by high rates of household air pollution [105], with average indoor levels of PM2.5 being approximately 100 $\mu g/m^3$ [106]. Due to the inefficient nature of these traditional cookstoves, smoke pollution and wood scarcity are concerns many residents and government leaders have.

To combat these challenges, a government initiative in 2012 distributed a two burner liquefied petroleum gas (LPG) stove and one tank of gas to each household, but these stoves go largely unused today due to the relatively high cost of LPG [104]. Most residents in the rural villages continue to use their biomass cookstoves because they can operate it at little or no cost, and are accustomed to cooking in that specific manner.

During the summer of 2014, we conducted field studies in the village of Locuto and Nuevo Reque to determine the necessary design requirements for an improved cookstove. In Locuto, the research team consisted of 5 engineers (two of whom were Peruvian) and a community guide. With the help of this guide, the research team visited twelve homes to interview and observe how the women interacted with their cooking stoves. The team also conducted six interviews with individuals employed making or selling charcoal, wood, or liquefied petroleum gas (LPG). In Nuevo Reque, 3 of those 5 engineers conducted an additional dozen interviews to collect similar information.

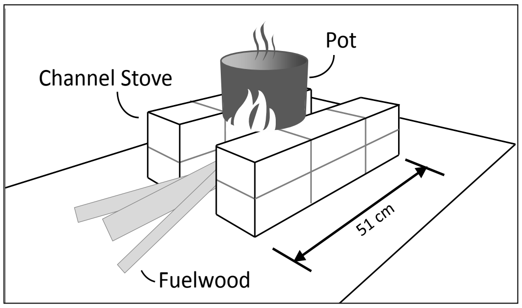
In response to the previous failed attempts to distribute improved cookstoves in the region, special care was given to identifying how to preserve the usability of the traditional cookstoves. Contextual information was gathered on topics ranging from local cooking practices and foods to the cost of certain commodities. The relevant results from these field studies are presented in this section.

6.1.1 Local Cooking Practices

In this portion of the thesis, field study results from the Tambogrande region are shared regarding the types of cookstoves used, customary foods, cooking habits, and local fuel sources.

Cookstoves- A variety of gas, charcoal, and wood cookstoves are all employed in this region with many residents owning and using more than one type of cookstove. The most common cookstove used, however, is the wood burning channel stove; comprising of two rows of clay bricks as illustrated in Fig. 6.1. The channel cookstove can be constructed at little or no cost and is very simple to operate. Most channel stoves are raised off the ground to a more comfortable height, such as on top of mud covered tables, as shown in Fig. 6.1.

Customary Food and Cookware- Rice and potatoes serve as the main food staples along with supplements of corn, fish, and other meats. These items are primarily combined into soups and cooked with aluminum pots ranging in diameter from 20 to 28 cm. Users cook with anywhere from one to three pots simultaneously and occasionally fry fish in small skillets. In addition, a significant amount of fuel is consumed in the preparation of tea, coffee, and chicha morada (sweetened corn



(a)


(b)

Figure 6.1: Schematic (a) and photo (b) of a traditional channel stove in Tambogrande, Peru.

based drink). It is also common in the region to prepare a large batch of chicha de jora (corn beer) once a week. Due to the large pots used (upward to 50 cm in diameter) and the long cooking times (7 hours), a second open fire is typically built outdoors for this task.

Cooking Habits- Most cooking is performed indoors with many of the households having two separate buildings; one for living and one for cooking. Lunch is the primary meal of the day and typically requires 30 minutes to start the fire and build a bed of coals, and then another one to two hours to cook the meal. Breakfast and dinner are typically smaller meals and may consist of reheated food or other simple dishes.

Fuel Sources- Fuels are both purchased and collected for free in this region. A tank of LPG costs approximately 35 Peruvian Nuevo Soles (∼11 USD). A 25 kg bag of charcoal costs approximately 30 Peruvian Nuevo Soles (PEN), or residents can purchase smaller quantities of charcoal for roughly 1 PEN. Wood fuel can also be purchased, costing about 1 PEN for three “sticks”. However it takes about four sticks to cook a large meal, so most people prefer to collect their own fuel at no cost.

Biomass fuels are gathered from the surrounding regions in the form of sticks and branches. Residents are concerned about the increasing difficulty associated with collecting free fuel and government leaders are worried about any associated negative environmental impacts. The sticks and branches collected range in diameter from 1.5 to 10 cm and up to one meter in length. Residents typically do not cut their fuel into small pieces before stoking fires. Dried leaves, scrap plastic, and paper are all used for kindling.

6.1.2 Customer Requirements for an Improved Cookstove

The data from the field studies allowed us to categorize the customer requirements into two categories; the characteristics of the channel stove that the residents find highly desirable and are essential to preserve, and additional cookstove characteristics they aspire to obtain.

Channel Stove Features to Preserve

The following cookstove characteristics are currently embodied in the traditional channel stove and should remain as requirements for any new or modified improved cookstove:

- *Pot Flexibility.* The improved cookstove retains the capability to cook with one, two, or three pots at a time. In addition, it accommodates pots ranging in diameter from 20 to 28 cm.

- *Easily Tended.* The improved cookstove is easy to load with fuel and maneuver the hot coals; similar to the case with the channel stove.

- *Fuel Flexibility.* The improved cookstove preserves the ability to burn the same variety of fuels as the channel stove, primarily long tree branches ranging from 1.5 to 10 cm in diameter.

- *Low Cost.* Because the channel stove can be constructed at little cost (the price of approximately 12 bricks), residents will have a difficult time paying large sums of money for expensive alternatives, thus the target cost should be less than 10 PEN. In addition, any modifications must retain the ability to burn fuel from free sources.

Additional Customer Requirements

Despite the considerable usability of the channel stove, residents identified several items that they did not enjoy about their current cooking situation. The top three additional characteristics to include with any improved cookstove design or modification would be as follows:

- *Decrease the Cooking Time.* Residents desire an improved stove that cooks more quickly than their current channel stove. Currently, it takes approximately 30 minutes to heat up the channel stove and an additional one to two hours to cook the remainder of the meal. The desire for quicker cooking time is one of the few reasons why residents occasionally cook with a gas stove.

- *Decrease the Amount of Fuel.* Since free fuel wood is becoming more scarce, and some residents have already begun paying for fuel wood, residents desire a stove that uses less wood. It is estimated that a reduction of at least 15-20% will be needed in order for users to perceive this benefit.

- *Reduce the Amount of Smoke.* Residents frequently commented on the discomfort that comes from indoor air pollution, as well as being impacted by the smoke from other households in the neighborhood.

6.1.3 Improved Design

Once the appropriate customer requirements were identified (as listed in the previous section), numerous design concepts were developed to satisfy those requirements. Because the primary design objective was to design a cookstove that would be well received, and not just achieve the highest levels of technical performance, a wide variety of concepts were considered. Ultimately, the design team determined that the greatest number of customer requirements were satisfied when design concepts deviated the least from the form and function of the channel stove. Instead of designing an entirely new cookstove that would be foreign to the residents, the aim became to modify the Peruvian channel stove by incorporating a mechanism that would improve the stove's efficiency without compromising the usability of its traditional design. The final design converged upon was a set of inexpensive, adaptable pot skirts that rest on top of the channel stove and partially encircle the cooking pot (see Fig. 6.2 and Fig. 6.3).

Since the traditional channel cookstove has a very low heat transfer efficiency, pot skirts were found to be one of the most effective ways to improve this deficit, compared to other options considered. Pot skirts, in general, function by directing the hot gases released during combustion to pass directly along the sides of the pot, which results in higher flow temperatures and higher heat transfer efficiencies [107]. An increase in heat transfer efficiency is ideal for users since it leads to

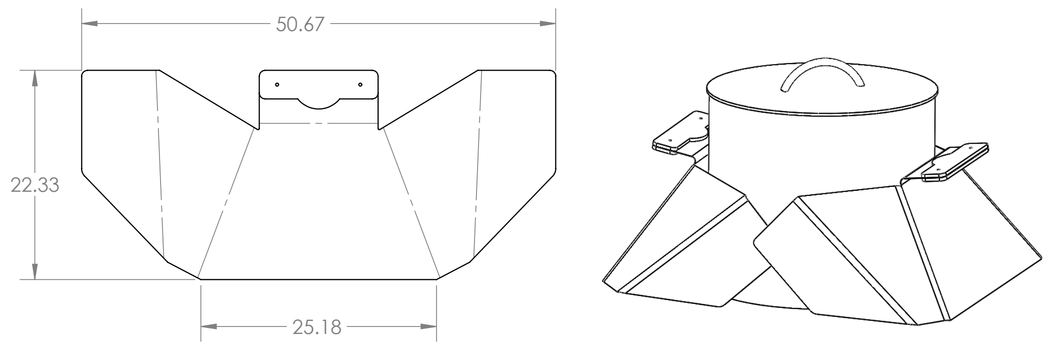


Figure 6.2: Schematic of the pot skirts, shown in their flattened and assembled forms. All dimensions in cm.

Figure 6.3: A picture showing the final prototype.

decreased cooking time and smoke reduction. The pot skirts also absorb some of the convective heat released by the gases and re-radiates it back to the combustion zone to promote more efficient combustion [108]. In the study by Wohlgemuth et al. [108], it was demonstrated that maximum skirt benefit is achieved with the addition of an insulating layer. However, in order to minimize cost and maintain affordability, no insulation was included in the design.

Each pot skirt used in this study is constructed from 24 gauge thickness sheet metal but other thicknesses may also be acceptable. It can be cut or stamped out of a single piece of metal, thus decreasing manufacturing costs. The two trapezoidal side panels are bent to lay against the sides of the cooking pot and force the hot air to circulate around the pot on all sides. The skirt also includes a wood covered handle which allows for easier placement and adjustment. The expected cost to manufacture one set of pot skirts is 3.78 PEN.

Although pot skirts have been incorporated with other improved cookstoves from around the world, they have often been problematic from a usability perspective. They are commonly restrictive in only allowing one size of pot, or are cumbersome for users to work with. This is driven by the need to achieve maximum technical performance. The pot skirts designed in this study attempt to overcome these drawbacks by allowing users to use any size of pot ranging from 20 to 32 cm, and allow for easy adjustment or temporary removal of the skirts. An additional difference compared to other pot skirts is that these pot skirts have been designed to be integrated directly with a channel stove and allow users to retain the ability to cook in their customary fashion. These features were all strategically chosen to increase usability, even at the cost of some technical performance.

6.2 Usability Field Experiment: Stove Testing and Evaluation

The pot skirts were subjected to a formalized testing process, involving both field tests with end users and controlled laboratory tests. The purpose of these tests were to determine 1) if the end users found the pot skirts to be highly usable, and 2) if the pot skirts make a difference in the technical performance of the stove (i.e. efficiency, fuel reduction, etc). Collectively, the answers to these two questions play a significant role in predicting the skirt's overall impact.

6.2.1 Laboratory Testing of the Channel Cookstove and Pot Skirts

To determine what degree the pot skirts increase the technical performance of the channel stove, a replicate channel stove was created at the biomass burn facility at Brigham Young University. The channel stove's efficiency, fuel consumption rate, and time to boil were measured under two scenarios: with and without the pot skirts. The results were then compared to determine statistical significance.

Laboratory Testing Procedure

The test procedure that was followed was according to the Water Boiling Test protocol (WBT) [109]. This test is a lab based test and provides for repeatable and low cost testing of biomass cookstoves. Because of its repeatable nature, it is an excellent test to determine the effect of certain design changes throughout the development process.

There are a variety of variations and options of the WBT that exist in academic literature. Therefore, we chose the variations that were most representative of the daily cooking conditions in Peru. The amount of water boiled during each test was 2.5 liters, compared to the more common 5 liters. A lid was placed on the pot throughout the duration of the tests as recommended by [4, 110, 111]. And since the presence of a lid significantly affects the analysis of the simmering phase, as highlighted by Ramn et al. [100], the simmering phase of the WBT was omitted. The amount of water boiled during each test was 2.5 liters, using 25.5 cm diameter pots.

Effort was taken to replicate the channel stove as accurately as possible. Clay bricks were used instead of cement bricks, and the height, width, and depth of the replica stove were set to match the common dimensions measured during the 2014 field study and as set forth in Table 6.1.

Table 6.1: Dimensions of the replica channel stove used during WBT tests.

Parameter	Dimension
Cookstove length	51 cm
Cookstove height	13 cm
Channel width	13 cm
Overall stove width	33 cm

It should be noted that WBT results presented here do not necessarily represent the channel stove's actual performance in the field, but are only accurate for comparing alternative designs tested in this particular lab setting. This disparity between WBT results and field use has been clearly documented by several previous authors [99–101]. Despite the limitations of the WBT in predicting actual performance, it is useful in selecting the most promising products for field trials, and thus we have employed it in this study [109].

Water Boiling Test Results

The results from conducting the WBT on the traditional channel cookstove, without modifications, can be found in Table 6.2. Results for both cold start and hot start portions of the test are presented. The WBT was then conducted again on the channel stove, but this time with the presence of the pot skirts. The results from these lab tests are presented in Table 6.3.

Table 6.2: Water Boiling Test results from testing the traditional channel stove.

	Cold Start			Hot Start		
	Value	Number of Samples	Standard Deviation	Value	Number of Samples	Standard Deviation
Thermal efficiency	9.19%	8	1.2	9.38%	12	1.78
Time to boil	20.20 (min)	8	3.16	19.96 (min)	12	5.35
Temp corrected specific fuel consumption	191.5 (g/liter)	8	27.23	165.5 (g/liter)	12	51.01

Table 6.3: Water Boiling Test results for the channel stove with pot skirts.

	Cold Start			Hot Start		
	Value	Number of Samples	Standard Deviation	Value	Number of Samples	Standard Deviation
Thermal efficiency	13.01%	8	1.51	12.91%	13	0.95
Time to boil	13.60 (min)	8	1.86	14.23 (min)	13	1.89
Temp corrected specific fuel consumption	136.38 (g/liter)	8	17.53	117.54 (g/liter)	13	19.44

6.2.2 Discussion and Analysis of WBT Results

To determine if there exists a significant difference in performance between the two test groups (the channel stove with and without pot skirts), a t-test comparison was performed. The results are presented in Table 6.4. Since the t-calculated values exceed the t-critical values (at a 95% level), we conclude that the pot skirts make a significant improvement for both hot and cold starts. Meaning, the pot skirts statistically improve the channel stove's thermal efficiency, reduce the amount of fuel required, and decrease the time required to boil water.

Table 6.4: Comparing the impact of pot skirts on the channel stove with t-test comparison testing at a 95% confidence interval.

	Cold Start			Hot Start		
	t-calc	t-critical (95%)	Percent change	t-calc	t-critical (95%)	Percent change
Thermal efficiency	4.20	1.76	41.7%	6.26	1.71	37.6%
Time to boil	4.51	1.76	-32.7%	2.15	1.71	-28.7%
Temp corrected specific fuel consumption	1.91	1.76	-28.8%	2.13	1.71	-29.0%

6.2.3 Field Testing Setup

During the summer of 2015, we traveled to the small community of Locuto, located in the Tambogrande district of Peru, to conduct field experiments (see Fig. 6.4). Fifty-four households, in different parts of the community, accepted the invitation to participate in the study. Participants were given one set of pot skirts, along with a brief tutorial of how to use the skirts. After using the pot skirts for at least a week in duration, the researchers returned and interviewed them. In total 42 households were interviewed.

During the follow up interviews, the researchers asked a series of predetermined questions, as well as observed the actual use of the pot skirts inside the kitchens. Pot skirts that received heavy

Figure 6.4: One of 54 households participating in the field study.

use showed significant amounts of heat discoloration and noticeable soot accumulation on the inside surface. These visual signs were used to check for efficacy and accuracy in the respondent's answers. Answers to the following questions were collected:

1. How well did the pot skirts interface with the traditional channel cookstove and pots?
2. What challenges or difficulties did the users experience?
3. How often were the pot skirts used?
4. Did the users perceive any benefits or disadvantages from using the skirts?
5. Were the users willing to purchase the pot skirts and at what price?

The answers to to these five questions are presented in the following section:

6.2.4 Field Testing Results

Q1-Interfacing with Traditional Dtove

Field studies revealed that the pot skirts were compatible with nearly all the channel stoves they were tested on. Meaning, the shape and size of the pot skirts fit as expected on the top surface of the channel stove, despite there being some variance in the size of each channel cookstove. In a few cases, the channel stoves were not long enough to accommodate more than two pots and the skirts, thus users would have to extend their stoves by simply adding additional bricks.

There were some minor difficulties with the differing pot sizes. The pot skirts were originally designed to work with pots ranging from 20 to 28 cm in diameter. Field studies confirmed that nearly every household had a pot this size and the pot skirts interfaced well with these sizes. However, nearly every household also had at least one pot smaller than 15 cm in diameter. Although the participants still noticed many perceived benefits, it was apparent to the researchers that the pot skirts' height made it cumbersome to work with the shorter, smaller pots.

Q2-User Difficulties

In response to the question of "Did you experience any difficulties?", five of the 42 participants reported the handles being too hot. Three of the households reported difficulty in using small pots. One additional participant each found the skirts to be cumbersome to use, dislike for the rusting of the steel, or the skirts seemed to get more ash in their food. Lastly, it was observed that of the 42 households, six of them attempted to use the pot skirts in the wrong configuration; placing the skirts vertically on one edge and leaning it against the pot.

Q3-Usage Amount

The amount the pot skirts were used over the course of the week is best described by the distribution outlined in Table 6.5. As seen, over 73% of the participants used the pot skirts regularly. There was however 26.2% of the participants that did not use the pot skirts. This is due to a variety of reasons. Four of the households were under the opinion that if they used it, they would be required to pay. Thus they did not use it. Two households did not use it because they cooked all of their meals that week with a gas stove. The remaining 5 households chose not to use it for unreported reasons.

Q4-Perceived Benefits

As part of the interviewing process, each participant was asked the open ended questions of "How did it go?" and, "Did you notice any difference?" Out of the 31 participants who had used the skirts at least once, 24 of them (77.4%) mentioned some type of perceived benefit. Some of them noticing several benefits. Their responses are summarized in Table 6.6. As shown in the

Table 6.5: The amount of usage the pot skirts received over the course of one week (n=42). Heavy use is defined as at least once a day. Moderate use is defined as 2 to 6 times per week.

	Number of Participants	Percentage
Heavy use	15	35.7%
Moderate use	16	38.1%
No or little use	11	26.2%

table, slightly over half of the participants who used the skirts noticed that the pot skirts cooked faster, while one-third also noticed a decrease in the amount of smoke. The category of “fire control” refers to participants’ observations that the skirts kept the fire together and prevented it from spreading out towards the end of the stove.

Table 6.6: The perceived benefits from those who used the pot skirts at least once (n=31).

	Number of Participants	Percentage
Faster cooking	16	51.6 %
Decreased smoke	10	32.3%
Fire control	7	22.6%
Decreased soot	1	3.2%
Better taste	1	3.2%

Q5-Willingness to Pay

Although the participants were allowed to keep the pot skirts free of charge as compensation for their participation, data on their willingness to purchase was collected as part of the interviews. The results are displayed in Table 6.7. Though efforts were taken to try and minimize the effect, it is likely that some of the participants heard they would be receiving the pot skirts for free prior to their interview, thus potentially influencing their responses.

Table 6.7: The willingness of all the participants to purchase the pot skirts (n=42) and at what price.

	Number of Participants	Percentage
Greater than 7 PEN	7	16.7%
Between 5 & 7 PEN	7	16.7%
Less than 5 PEN	2	4.8%
Not willing to purchase	23	54.8%
Unknown	3	7.1%

6.2.5 Field Experiment Conclusions

The results from the 2015 field study allow us to draw conclusions regarding whether the end-users found the pot skirts to be highly usable and their initial acceptance of the product. To draw conclusions about the pot skirts' usability, we reference the fact that only 10 of the households reported some type of difficulty with the pot skirts' fit, form, or function with the traditional channel stove.

We also reference the fact that the pot skirts satisfy six of the seven customer requirements outlined in Section 6.1.2. The exceptions to this include that many of the customers did not indicate a willingness to pay for the pot skirts and that the pot skirts do not work well with small, short pots, even though the initial customer requirement did not call for this. With all these things considered, we conclude the pot skirts were found to be highly usable.

6.3 Usability Field Experiment: Discussion

Based upon the results presented, for both field and laboratory testing, we conclude that the pot skirts are positioned to make an impact in the Locuto community: meaning they have the capability to reduce indoor smoke pollution and decrease cooking time when compared to traditional methods, and achieve a higher rate of use and adoption compared to other cookstoves previously introduced in this community. The pot skirts minimally disrupt the customary way of cooking, and significantly improve the technical performance of the stove. We recognize though that the pot skirts are not flawless. Areas of future work include altering the design to work better with smaller pots, especially those that are short in height. In addition, the usability of the pot skirts could further be enhanced by modifying the handles such that they are not as hot during operation.

We acknowledge that these pot skirts combined with the channel stove do not achieve the same levels of efficiency or cleanliness obtained by other advanced improved cookstoves on the market [28, 30]. However, by preserving the usability of the traditional channel cookstove, higher adoption rates are likely to occur; a tradeoff that we believe is more important than achieving the highest technical performance. As an example, consider the following scenario.

In the Locuto community, our estimates predict approximately 75% of the residents burn biomass in their channel cookstoves daily. With approximately 300 households, and each household consuming about 16 kg of fuel each week, this totals approximately 4,800 kg of wood burned weekly in the community.

If a new top-of-the-line improved cookstove, that reduced wood consumption by 60% were introduced, it would be capable of decreasing fuel use by 2,880 kg per week if users exclusively cooked all their meals with the new stove. But, as with other advanced biomass cookstoves, adoption rates may be as little as 15% of the households, or only 15% of the meals cooked. That results in a fuel reduction of only 432 kg of wood per week. In comparison, consider the proposed pots skirts presented in this article, that potentially reduce fuel consumption up to 28.8% (using the rough assumption that field performance is similar to the WBT laboratory test results). In order to achieve the same amount of overall fuel savings as compared to the top-of-the-line model, only 31.3% of the community would need to adopt the pot skirts–a number potentially attainable based upon the results of this study.

We realize that such an illustration makes some simplifying assumptions, but the principle is clear; if only a few people adopt an improved cookstove, it is very difficult to make an impact, regardless of how efficient or clean the cookstove is. Therefore, our emphasis has been to design a cookstove that is easily adoptable. We did this by creating a product that can integrate directly with the traditional cookstove already in use, and allow it to use the same types and sizes of fuel, as well as the same sizes and number of pots.

We do not view these pot skirts as the ultimate solution to the regional problems these people face due to biomass cooking. The ideal situation is for the residents to move up the so called energy ladder and start cooking with cleaner fuels and technologies. But, as it has been documented in other sources, people do not make this transition in just one step [112]. They employ a variety of transitional technologies first, such as improved biomass cookstoves. Thus, the pot skirts presented in this article provide one of those transitional steps to help users recognize the benefits that come from cooking with cleaner, and more efficient methods.

This experimental study has primarily been focused on the design of improved cookstoves and how a usability focused design has the potential to achieve higher adoption rates compared to a technologically focused design. However, a cookstoves design is not the only variable that determines whether it will be adopted or not. Other authors have hypothesized a wide variety of social, environmental, and economic factors that also go into influencing adoption rates. Such factors include education levels [10], occupation [14], household income [11], household decision making processes [12], and many others. Thus we cannot definitively predict what the long term adoption rates of these pot skirts would be without years of actual data.

CHAPTER 7. CONCLUSIONS

The primary focus of this thesis was to investigate the following hypothesis: *If the design of improved cookstoves are primarily optimized for usability, while having at least some technical improvement over traditional stoves, then greater impact can be achieved.* In this paper, we define impact to be the direct result of the level of adoption achieved as well as the improvement in the performance variables of interest (i.e. efficiency, emissions, etc). The key method employed to test this hypothesis was to design a new usability-optimized cookstove for Locuto, Peru, and then assess the resultant impact on the community. If the impact is greater than the impact achieved by other cookstove projects around the world, then this provides favorable evidence towards accepting the above-stated hypothesis.

7.1 Revisiting the Six Research Questions

In Chapter 1, six research questions were set forth as a road map to testing this hypothesis. These questions were then explored and studied in later chapters. In this section, these six questions will be revisited along with summarizing the key findings and results.

Question 1. In the context of improved cookstoves, what does it mean to design for usability?

The answer can partially be described by ISO 9241-11 which defines usability as; *the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use [44].* This thesis further built upon this definition by demonstrating how this applies to the context of improved cookstoves. Clarity was brought to what types of "goals" end users are trying to accomplish, and demonstrated that user satisfaction is heavily dependent on how closely the new cooking stove mimics or exceeds the form, function, and performance of the traditional stove it is replacing. As an illustration, in Locuto, Peru the residents judge the usability of any new cooking device by the number of pots it could heat at one time, the types and sizes of fuel that could be used, the ease by which the fire could be maintained, and how quickly it takes to cook a customary meal. Collectively, designing for usability means to design the cookstove in such a way to achieve maximum levels of use. Thus, the most important variable in measuring the usability of a cookstove is to measure its long term adoption rate.

Question 2. What barriers/challenges have prevented designers from being successful at designing more usable cookstoves?

This thesis identified several challenges that have negatively impacted the usability and cultural acceptance of new cookstoves. First, there often exists a large physical distance between the design teams and the end users, resulting in a lack of customer feedback in the design process as well difficulty in simulating real life test conditions. Second, there is a large cultural difference between design teams and end users, thus engineers tend to make simplifying assumptions in the design process. Third, the heavy emphasis placed on improving cookstove efficiency (and other technical aspects) in the literature, media, and by funding organizations, has caused many design teams to under-appreciate other critical cookstove characteristics that are essential to the customer. Lastly, designing more usable cookstoves is very conditional to the vast array of customer needs and differing circumstances that exist around the world. Thus, it is much easier to design cookstoves that meet and achieve clear standards (i.e. efficiency & emission levels) than it is to design to the more subjective standard of usability.

Question 3. What are the end user needs that should be considered with a usability centered approach?

Authors in the more recent years have begun to emphasize that improved cookstoves need to do a better job of meeting end user needs. Until now, there hasn't been a concerted effort to educate designers and engineers what these end user needs might encompass. This research aimed to fill this gap by providing a list of the most common global and local needs that should be considered in the design process. A brief summary is provided here as published by Thacker, Barger, and Mattson in [22].

Global market requirements. The cookstove characteristics that were found to be desirable by a large percentage of all people and places.

- The cookstove saves fuel

- The cookstove improves air quality
- The cookstove is flexible with fuel type
- The cookstove cooks quickly
- The cookstove accommodates local cooking practices
- The cookstove is easily maintained
- The cookstove can be left unattended
- The cookstove is aesthetically pleasing
- The cookstove is affordable
- The cookstove is safe

Local market requirements. Cookstove characteristics that are unique to only certain regions or certain circumstances.

- The cookstove provides space heating
- The cookstove heats hot water for non-cooking tasks
- The cookstove fumigates insects
- The cookstove is portable
- The cookstove provides light

Question 4. How do end user needs vary across regions, within communities, and within households?

This thesis identified several regional, community and household factors that in large measure determine the end user's needs. Factors that differ with different regions include; food types, fuel types, climate, and kitchen configuration. All of which significantly impact user need and should be considered in cookstove design. Within a single community, user needs will vary drastically based on the size of the household, and the economic status of a household. Within a single home, cookstove use will depend on the meal type (breakfast, lunch, or dinner), size of the meal, the food being prepared, the season, fuel type available at that given time, and cooking equipment being used. Engineers and designers need to be cognitive of all these factors to ensure that cookstoves appeal to the target customer.

Question 5. How should the design process be adjusted in order to overcome these challenges and achieve a more user friendly result?

There are many standard methodologies in today's general design literature but none of them account for the unique challenges and barriers that cookstove designers and engineers face. The five step methodology presented in this research helps identify, extract, and then apply the customer needs in such a way that design teams, regardless of their experience with the customer's foreign culture, can properly focus their energy and prioritize their efforts on developing cookstoves that are user centered.

More specifically, the methodology presented in this thesis provides guidance to engineers on how to accurately collect and interpret customer need statements, a skill that most engineers are not formally trained in. Additionally, this methodology uses a performance matrix as a means to translate broad market requirements into specific, unambiguous performance requirements that design team members can work towards, regardless of their involvement in earlier stages of development. The performance matrix is also advantageous in that it easily accommodates both the qualitative and quantitative inputs associated with cookstove designs.

This methodology also sheds light on the importance and role of testing during the cookstove design process. Previously, the primary emphasis of testing has been to determine a cookstove's efficiency and other technical capabilities. While this type of testing is still valid and has a role in the development process, this methodology heavily emphasizes that the role of testing is to 1) Check if the cookstove design satisfies the customer needs established and 2) Are those initially identified customer needs accurate of what will truly be an acceptable stove to the end users.

Question 6. When using the modified design process, how are the resultant cookstoves different, and do these cookstoves have a greater chance for adoption and subsequently higher impact?

One important outcome of this research is that a usability-focused approach encourages design teams to examine a broader set of design solutions than would normally be considered. This was illustrated in the case study in which a new cooking device was designed for the residents living in Locuto, Peru. The resultant solution is a set of inexpensive pot skirts that can be incorporated with their traditional stove, instead of a modern improved cookstove. These pot skirts improve the thermal efficiency of the traditional cooking stoves by 41.7%, decrease fuel consumption by 32.7%, and decrease time to boil by 28.8%. Though these technical results may be less than other highly advanced cooking stoves, the advantage these pot skirts provide is the high potential for adoption, and thus a higher potential for impact.

Upon completion of the Locuto experiment, comparisons were made between the potential impact of the pot skirts compared to the potential impact of high performing improved cookstoves. If a new top-of-the-line improved cookstove was introduced into the community of Locuto, it likely would be adopted by only 15% of the households, or be used only during 15% of the meals cooked (based upon adoption results from other cookstove projects [10–12] This results in a fuel reduction of 432 kg of wood per week in the community. On the flip side, in order to achieve the same amount of fuel reduction, the pot skirts would only have to be adopted by 31.3% of the community – a number we feel is easily attainable based upon the results of the study, thus indicating high levels of usability. The results of this study were published by Thacker, Barger, and Mattson in the Journal of Development Engineering [23].

7.2 Limitations and Future Work

Long Term Implications of Research. The primary hypothesis posed at the beginning of this thesis is that greater adoption, and therefore greater impact, can be achieved if more priority is given to the usability of an improved cookstove during design. Unfortunately, drawing scientifically based conclusions about long-term adoption rates requires long-term studies– something we didn't have the luxury of during the course of this research. Therefore, we must exercise caution in interpreting the results from our short term study.

There is, in general, a great need for monitoring the long term adoption and impact of any improved cookstove program. Literature is lacking in such data. Specific to this study, it would valuable to monitor long term how the people of Tambogrande, Peru continue to interact with the pot skirts. Do they continue to use them as prescribed? Or do the users start modifying them to better suit their needs?

Adoption. It is important to note that an improved coookstove's physical design is just one of many variables that potentially impact long term adoption rates. Things such as customer's education level, community and regional politics, implementation strategies, and others, are all factors that various authors have contributed to poor adoption. A usability focused design is just one of several variables that must be managed in order to achieve high impact. Trying to identify which factors are the largest contributors to low adoption rates is a difficult objective, and an area that can benefit from further study.

New Methodology. In this research, a new design methodology was presented to help overcome many of the barriers that cookstove designers and engineers face. We believe this isn't the only correct methodology, and that many other methodologies should be developed in the years to come. We encourage authors of such methodologies to make them publicly known so that collectively the cause of improved cookstoves can be furthered.

Additionally, the ideas and principles of the methodology presented in this thesis would become more robust if tested in additional regions besides Northern Peru. While we found the results to be satisfactory in Tambogrande, Peru, it is possible that if this same methodology was applied to other regions and cultures the same positive result may not occur.

7.3 Concluding Remarks

With millions of people dying each year from the negatives side effects of cooking over open fires, the world is in great need of cleaner cooking solutions. Right now though, the world doesn't need just cleaner and more efficient biomass cookstoves– the world needs cooking technologies that can be incorporated into the user's customary way of cooking and achieve long lasting impact. In this research we advocate that a primary step in achieving this goal is that the design of cooking solutions should be optimized for usability, and not just for technical performance.

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