



All Theses and Dissertations

2017-04-01

Principles and Insights for Design for the Developing World

Amy Eleanor Wood
Brigham Young University

Follow this and additional works at: <https://scholarsarchive.byu.edu/etd>

 Part of the [Mechanical Engineering Commons](#)

BYU ScholarsArchive Citation

Wood, Amy Eleanor, "Principles and Insights for Design for the Developing World" (2017). *All Theses and Dissertations*. 6322.
<https://scholarsarchive.byu.edu/etd/6322>

This Dissertation is brought to you for free and open access by BYU ScholarsArchive. It has been accepted for inclusion in All Theses and Dissertations by an authorized administrator of BYU ScholarsArchive. For more information, please contact scholarsarchive@byu.edu, ellen_amatangelo@byu.edu.

Principles and Insights for Design for the Developing World

Amy Eleanor Wood

A dissertation submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy

Christopher A. Mattson, Chair
Spencer P. Magleby
Carol J. Ward
Randy S. Lewis
Matthew R. Jones

Department of Mechanical Engineering
Brigham Young University

Copyright © 2017 Amy Eleanor Wood

All Rights Reserved

ABSTRACT

Principles and Insights for Design for the Developing World

Amy Eleanor Wood
Department of Mechanical Engineering, BYU
Doctor of Philosophy

This dissertation collects principles and insights from various sources related to design for the developing world. These principles and insights form part of the foundation that can guide other engineers working in this area. The sources are the published literature, practitioners, non-governmental organizations, and our own field studies.

From the engineering literature, we identified nine principles to guide engineers as they design poverty alleviating products for developing communities. Each principle is articulated, supporting literature is described, an in-depth example from the literature is given, followed by suggestions for how the principle can be applied to day-to-day engineering activities.

Next, the work from engineering practitioners is studied. Information from various field reports was analyzed, a list of seven common pitfalls was derived, and the Design for the Developing World Canvas is introduced. This tool is similar to a Business Model Canvas, but it focuses on the product development process rather than the development of a business model. The Design for the Developing World Canvas can be used by design teams to facilitate discussions and make decisions that will allow them to avoid the common pitfalls identified.

A case study is then shared from a non-governmental organization called WHOlives.org about their experience with the Village Drill, a human-powered machine that digs boreholes for water wells. The case study outlines the development of the drill, a timeline of its implementation in 15 countries across three continents, specific values related to cashflows of the organization, and a conservative estimate of their impact in developing communities.

A study of our original research conducting field studies using a technique called ethnography is then shared. This study was conducted in four countries on four continents and shows the impact of various conditions on the ability of the design team to collect information that is useful for making product development decisions. The conditions in this study include cultural familiarity, language fluency, gender and age of the respondent, information source type, use of prototypes, and others. The results can guide design teams as they make decisions about who to include on the design team, which projects to pursue, and how to conduct their own field studies.

Lastly, conclusions related to design for the developing world are made based on the work presented and potential areas of future work are outlined.

Keywords: design for the developing world, engineering for global development, design principles, engineering principles, cross-border design ethnography, resource-poor customers

ACKNOWLEDGMENTS

Many people have supported me as I've completed this research and I'm grateful to each of them. I'm particularly grateful to my sweet husband, Charles, who constantly encouraged and supported me, participated in some of this research with me, spent many long nights discussing projects and papers, and spent many afternoons with our daughter while I completed this work.

I'm grateful to my committee chair, Christopher Mattson. His expertise in product design and his desire to use that expertise to alleviate poverty made this work possible. It has been an honor to work with him and I'm very grateful for his guidance.

I'm also grateful to my peers in the lab for their respect and help with this research, particularly to Kendall Thacker and McCall Barger for helping test the Design for the Developing World Canvas and Jeffrey Allen for his wisdom and guidance.

I'm very grateful to each of my committee members, specifically to Carol Ward for sharing her expertise in ethnography and for guiding me through my first coding experience, to Randy Lewis for providing an opportunity through the Global Engineering Outreach class for me to discover and cultivate my interest in design for the developing world, to Spencer Magleby for his encouraging words, advice, and enthusiasm for this work, and to Matthew Jones for his support of and commitment to engineering for global development.

Many other researchers have made the field studies presented here possible. I'm grateful to Charles Wood, Zachary Epley, Margaret Sabey, and Pierce Arnett for their sense of adventure and willingness to help. I'm also grateful to our many community partners who facilitated these field studies.

I would also like to acknowledge the National Science Foundation for the funding received through grant CMMI-0954580. This funding allowed me to have several international experiences that taught me things I could not have learned from my desk in the lab.

Lastly, I recognize the hand of the Lord guiding this work. I'm grateful for that guidance in my academic pursuits and in all other areas of my life.

TABLE OF CONTENTS

LIST OF TABLES	vii
LIST OF FIGURES	viii
Chapter 1 Introduction	1
1.1 Motivation for This Research	1
1.2 Objectives of This Dissertation	3
1.3 Principles from the Engineering Literature	6
1.4 Insight from Practitioners	7
1.5 Case Study from a Non-Governmental Organization	9
1.6 Insights from Our Field Studies	10
1.7 A Note on Terminology	12
Chapter 2 Nine Principles for Design for the Developing World as Derived From the Engineering Literature	14
2.1 Chapter Overview	14
2.2 Introduction	14
2.3 Nine Principles for Effective Design for the Developing World	16
2.3.1 Principle 1: Co-design with people from the specific developing world context encourages designer empathy, promotes user ownership, and empowers resource-poor individuals.	17
2.3.2 Principle 2: Testing the product in the actual setting is an essential part of design for the developing world, not merely a final step.	21
2.3.3 Principle 3: Importing technology without adapting it to the specific developing world context is ineffective and unsustainable.	23
2.3.4 Principle 4: Both individuals in urban and rural contexts can benefit from poverty alleviation efforts.	26
2.3.5 Principle 5: Women and children are more affected by poverty alleviation efforts than men.	28
2.3.6 Principle 6: Project management techniques that are adapted to the specific developing world context enable a more effective and efficient design process.	30
2.3.7 Principle 7: Products for the developing world have greater impact when contextualized, developed, and implemented by interdisciplinary teams.	32
2.3.8 Principle 8: Cooperation with governments and local influencers contextualizes and enables poverty alleviation plans.	35
2.3.9 Principle 9: There are existing distribution strategies that can be used to successfully introduce products into developing world markets.	38
2.4 How the Nine Principles Relate to Traditional Design Principles	41
2.4.1 The Generic Solution Finding Process	41
2.4.2 The Problem and Solution Context	43
2.4.3 The Team	45

2.5	Concluding Remarks	46
2.6	Additional Information for Analysis of Traditional Design Principles	48
Chapter 3 Design for the Developing World: Common Pitfalls and How to Avoid Them 50		
3.1	Chapter Overview	50
3.2	Introduction	50
3.3	Research Method	51
3.4	Pitfalls	53
3.4.1	Pitfall 1: Lacking the contextual knowledge needed for significant impact	55
3.4.2	Pitfall 2: Neglecting to make a plan for or developing partners for long-term sustainability	57
3.4.3	Pitfall 3: Assuming the needs of the customers being served	60
3.4.4	Pitfall 4: Not making a plan for or developing partners for manufacturing	61
3.4.5	Pitfall 5: Lacking skills or expertise for a specific project	63
3.4.6	Pitfall 6: Miscommunicating or failing to develop trust with local stakeholders	64
3.4.7	Pitfall 7: Forgetting that communities change over time between field visits	65
3.5	Design for the Developing World Canvas	66
3.5.1	Structure of the Canvas	67
3.5.2	General Considerations: Contextual Factors and Partners	68
3.5.3	Impact	69
3.5.4	Customer	70
3.5.5	Product	70
3.5.6	Delivery	71
3.5.7	Manufacturing	72
3.5.8	Revenue Model	72
3.5.9	How the Canvas and Pitfalls are Linked	73
3.6	Case Study in Using the Canvas	76
3.6.1	Background	76
3.6.2	Use of the Canvas	77
3.6.3	Benefit of Using the Canvas	77
3.7	Discussion and Concluding Remarks	78
Chapter 4 Village Drill: A case study in engineering for global development with five years of data post market-introduction 80		
4.1	Chapter Summary	80
4.2	Engineering for Global Development and the Need for Case Studies	80
4.3	The Village Drill Case Study	81
4.3.1	Case Study Introduction	83
4.3.2	Village Drill Timeline	84
4.3.3	Product	86
4.3.4	Customer	89
4.3.5	Impact	90
4.3.6	Manufacturing	95

4.3.7	Delivery	95
4.3.8	Revenue Model	96
4.3.9	Uncertainty Analysis	99
4.4	Discussion and Conclusion	101
4.5	Raw Data Used for Case Study	104
Chapter 5 An Experiment in Cross-Border Design Ethnography in the Developing World		108
5.1	Introduction	108
5.2	The Experiment	111
5.2.1	Description of the Conditions	111
5.2.2	Description of the Locations	112
5.2.3	Description of Ethnographic Activities	114
5.2.4	Description of the Timeline	115
5.3	Analysis	116
5.3.1	Post Field-Study Data Processing	116
5.3.2	Statistical Analysis	120
5.3.3	Determining the Accuracy of the L-MH and M-H Models	122
5.3.4	The Odds Ratio	123
5.4	Results and Discussion	124
5.4.1	Influence of Condition	125
5.4.2	Influence of Ethnographic Activity	135
5.4.3	Influence of the Source of Information	138
5.4.4	Influence of Gender	140
5.4.5	Influence of Age	142
5.4.6	Influence of Prototypes	144
5.4.7	Need Statements	144
5.5	Conclusions	145
Chapter 6 Conclusions and Future Work		150
6.1	Chapter Overview	150
6.2	Contributions	150
6.3	Conclusions from Principles Derived from the Engineering Literature	155
6.4	Conclusions from Pitfalls Derived from Practitioner Field Reports	156
6.5	Conclusions from the Village Drill Case Study	157
6.6	Conclusions from the Experiment in Cross-Border Design Ethnography	158
6.7	Understanding Context	159
6.8	Understanding Customer Needs	160
6.9	The Need for Partnership	161
6.10	Future Work	162
REFERENCES		166

LIST OF TABLES

2.1	Summary of Principles	46
2.2	Traditional Design Principles for the Four Steps of the Generic Solution Finding Process	49
3.1	The 7 common pitfalls with the percentage of statements from the reports analyzed that reflect each pitfall.	54
3.2	All non-weak correlations observed between pitfalls.	55
3.3	Link between pitfalls and sections of the canvas	73
4.1	Village Drill Measures After 5 Years ($n_t = 65$)	82
4.2	Uncertainty Analysis Results (Including all Time Periods)	100
4.3	Raw data used in the Village Drill case study.	106
4.4	Raw data used in the Village Drill case study continued.	107
5.1	Summary of Coded Data Counts.	120
5.2	Results from L-MH Model. The predictor in the first column is being compared to the predictor in the second column. For example, the first row is interpreted as “the community partners only condition is 1.50 ($p < 0.001$) times more likely to give medium or high usefulness information than the language fluency and community partners condition”	126
5.3	Results from M-H Model. The predictor in the first column is being compared to the predictor in the second column. For example, the first row is interpreted as “the language fluency and community partners condition is 5.00 ($p < 0.001$) times more likely to give highly useful information than the community partners only condition”	127
5.4	Results from Additional Models 1 and 2. These show the L-MH Model and M-H Model respectively when the condition predictor was replaced with the country predictor. The predictor in the first column is being compared to the predictor in the second column. For example, the first row is interpreted as “information collected in India is 9.51 ($p < 0.001$) times more likely to be of medium or high usefulness than information collected in Spain”	130
5.5	Results from Additional Models 3 through 6. This table lists results for each model with either the condition or country predictor included. The predictor in the first column is being compared to the predictor in the second column. For example, the first row is interpreted as “information collected in the community partners only condition is 3.40 ($p < 0.001$) times more likely to be of medium or high usefulness than information collected in the language fluency and community partners condition”	131
5.6	The number of excerpts in each category of usefulness by country.	133
5.7	The number of excerpts in each category of usefulness by ethnographic activity.	137
5.8	Percentage of ethnographic activities completed by each gender group.	140
5.9	Number of excerpts from each gender by usefulness.	141
5.10	Number of excerpts in each need statement category by gender group.	145

LIST OF FIGURES

2.1	Three concentric ovals representing (i) a generic solution finding process (center), (ii) the context for the problem and solution (inner ring), and (iii) the team that contextualizes and develops the solution (outer ring). This figure facilitates the discussion in Sec. 2.4.	42
3.1	The Design for the Developing World Canvas. Each section of the canvas represents an essential part of product development that if thoughtfully considered will help design teams avoid common pitfalls of designing for resource-poor individuals.	67
4.1	Village Drill: (a) in use in Tanzania, (b) description of basic function, (c) detail of drilling bit and chip removal.	81
4.2	Timeline for product development and delivery/drilling milestones.	85
4.3	The major subsystems and parts of the Village Drill. The structure divides into 5 parts; the base, the boom, the wheel support, and two vertically oriented beams to give the boom height. The input wheel has a center hub (welded) with eight spokes that extend from it and are secured by eight cross members. The drill string includes the swivel, Kelly bar, and many short (meter-long) pipe segments and couplers that are added to the drill string as the borehole deepens. The Village Drill disassembles into the pieces shown for transport to and from the job site.	88
4.4	Time series plot showing productivity measures and wells in service.	96
4.5	Time series plot showing the primary impact measures. The total number of people-months of water served is 4,129,945. The number of people who have access to a well (at time period 65 ($n_t = 65$)) with a functioning pump equals 188,176, while the number of people who could have access to water if all pumps were serviced equals 316,281.	97
4.6	Time series plot showing incomes and cashflow. Zero income shown as baseline.	99
4.7	Histogram resulting from the uncertainty analysis carried out on the cumulative number of people-months of water provided (n_{pmws}). The mean and standard deviation for this data are shown in Table 4.2.	102
5.1	Results for condition predictor.	128
5.2	Results for Additional Models 1 and 2.	129
5.3	Results for Additional Model 3 – L-MH analysis of the open-ended ethnography data for condition and country predictors.	132
5.4	Results for Additional Model 4 – M-H analysis of the open-ended ethnography data for condition and country predictors. There were insufficient data to run this model.	134
5.5	Results for Additional Model 5 – L-MH analysis of the problem-area focused ethnography data for condition and country predictors.	134
5.6	Results for Additional Model 6 – M-H analysis of the problem-area focused ethnography data for condition and country predictors.	135
5.7	Results for the ethnographic activity predictor.	137
5.8	Results for the source predictor.	139
5.9	Results for the gender predictor.	141

5.10 Results for the age predictor.	143
5.11 Results for the prototype predictor.	144
5.12 Results of the need statement predictor.	145

CHAPTER 1. INTRODUCTION

1.1 Motivation for This Research

Between 10 and 20% of the world's population lives in extreme poverty [1], [2]. Resource-poor individuals face numerous challenges, many of which could be solved through appropriately designed and affordably priced products [3], [4]. There is no shortage of needs and there is no shortage of opportunity to deliver as resource-poor individuals represent a \$5 trillion market [5]. Many have observed and reported on the tremendous opportunity for business in these markets [6]–[16]. There also appears to be an increasing supply of engineers interested in pursuing this work [17]. Engineers Without Borders membership in the US, for example, increased 500% between 2005 and 2011 [18] and the Editor-in-Chief at ASME Magazine describes product design for the developing world as an area of research “worth pursuing” in 2011 [19]. There is, however, a shortage in our understanding of how to effectively design products to serve this market in a way that produces lasting impact.

Recently, there has been a surge of effort to reach resource-poor markets from leaders in business, social science, international development, and engineering. Most prominent in the engineering literature is the work carried out by electrical and civil engineers to design and install electrical, water, and sanitation systems for resource-poor *communities* [20]–[27]. In contrast, very little work has been published in the area of product design for resource-poor *individuals* [28]–[31]. Considering the challenges resource-poor individuals face, innovative products have the potential to make a significant impact. The term *product* is used in this dissertation to describe any consumer good that is purchased by an individual or household. While mechanical engineering is not the only professional field with training in product design, mechanical engineers are well-trained in mechanical design, optimization, and manufacturing techniques – all of which may be needed to produce effective product solutions. Unfortunately, the opportunity and urgency to find solutions that alleviate poverty are far greater than the number of mechanical engineers currently

involved. More impact is needed. Many engineers, including ourselves, have attempted to design products for resource-poor individuals in the developing world but few of these products have had the positive and widespread impact the engineers intended [32].

Over the last several decades, there have been many different approaches to helping resource-poor individuals in the developing world. The first of these is described by Nieuwma as Technology Transfer [33]. With this approach, heavy machinery such as farming equipment was sent to developing countries. This approach attempted to leverage the advances in technology used in developed countries to help people in developing countries. Over time, the machinery needed repair and it became clear that there was no system in place for maintenance. Without this long-term support, this approach did not have the intended impact.

Akubue [34] indicates that importing large-scale technologies from the developed world does not generally help alleviate poverty in the developing world because these technologies are capital-intensive in a market with little capital. Further, costly labor-saving technologies are not valued in communities with excess labor capacity. Ultimately, according to Akubue, the importation of large-scale technologies encourages urbanization and can help resource-poor individuals in urban settings, but it creates a larger income gap between the rural and urban communities.

In the 1970's and 1980's, the work of Schumacher, Papanek, and others started a movement known as Appropriate Technology [35]–[37]. Akubue supports the Appropriate Technology movement, which he describes as a “development approach that is aimed at tackling community problems” as opposed to individual problems. It focuses on using the resources available (labor), not scarce resources (capital, skilled labor) [34]. This movement led to many products that were jointly owned by all members of a community and that required a large amount of time and physical labor to operate [38].

Fisher [38] and Polak [39] came years later and expressed the belief that the only way to effectively alleviate poverty is to help people make money. This idea of income-generating products still has much support today [22], [40]. Fisher indicates that poverty-alleviating products need to be individually owned and cared for – rather than community based – to have impact. He and others argue that with community owned projects, there is no penalty for people who do not contribute and no reward for people who do [38]. Fisher also stated that it is not possible

to have a sustainable business serving resource-poor customers and that additional income from philanthropies or NGOs is necessary to support product development activities.

In the last decade, several private companies have found a way to build a sustainable business while meeting the needs of resource-poor customers [41] using an approach commonly known as Social Entrepreneurship. These companies focus on spending time in the field and on collecting customer feedback. This focus on the customer has been the key factor leading to their success [41], but this customer-centric approach takes a vast amount of resources and can be difficult to replicate, particularly when those conducting the research come from a different culture and background than the customers they intend to serve.

Overall, there have been and continue to be many approaches to solving the problems associated with poverty and as a research community, we are still testing and learning which approach is best for each situation. Many researchers and practitioners have worked in this area but there is little rigorous academic research to guide engineers wanting to design products for resource-poor individuals that alleviate the pains of poverty.

1.2 Objectives of This Dissertation

The main research question this dissertation seeks to answer is: How can engineers design products that have more significant and lasting impact on alleviating poverty in the developing world? Our hypothesis is that principles and insights to guide the design process in this context can be gleaned from at least three sources: (i) the engineering literature, (ii) the experiences of practitioners working in developing communities, and (iii) our own experiences applying ethnographic techniques. This hypothesis was tested in four parts: (i) a thorough review of the literature to identify themes and principles, (ii) a review of field reports from practitioners to identify common failures modes and suggestions for overcoming them, (iii) an in-depth study with one practitioner of one product and its implementation in 15 countries, and (iv) applying ethnographic techniques under a variety of conditions in four countries on four continents.

Part 1, a review of the engineering literature, resulted in nine themes that were articulated as design principles. Each of these principles was supported by many independent sources, prompting us to conclude that each is significant and helpful in guiding design teams. Part 2, an analysis of a broad range of unique products, resulted in seven themes that were articulated as pitfalls. These

pitfalls are common failure modes that several independent practitioners experienced. Because so many had already experienced them, we concluded that others were likely to do the same. Articulating these failure modes as pitfalls allows them to be easily shared with and avoided by other engineers. To further enable engineers to avoid them, we developed a tool called the Design for the Developing World Canvas that can guide design teams through decisions in a way that avoids the pitfalls. Part 3 is a case study presenting one specific product called the Village Drill. Studying the implementation of this product in a developing world setting provides several insights for other engineers, such as a realistic time line for impact, the resources invested before impact was achieved, the extent of product sustaining required to create lasting impact, and a conservative model for estimating impact. Part 4, applying ethnographic techniques under a variety of conditions in four unique locations, was planned after identifying several themes in the Parts 1 through 3. One theme was that engineers lacked an understanding of the context and of the customer's needs. In an attempt to understand the context and needs more accurately, a tool called ethnography was experimented with. We wanted to determine how the usefulness of ethnographic methods would change with changing conditions, such as cultural familiarity and language fluency. This study resulted in 6,050 pieces of information that was evaluated using a rigorous statistical analysis and provides several useful insights for design teams planning a cross-border ethnographic study.

While practitioners have been designing products in an attempt to alleviate poverty for decades, design for the developing world is a very young area of formal academic research. There have been many products designed and documented in the engineering literature but there have been few studies that take each of these individual products and experiences and synthesize them into more generally applicable principles and insights that can be used by other engineers [42]–[44]. These general principles and insights serve as a foundation for the research community to build upon but remain largely absent from the literature and common practice. This gap in the literature and in the understanding of the research community is the gap this dissertation aims to fill.

Through the literature reviewed and our own experiences, we've concluded that most developing world products don't fail for technical reasons; they typically fail because the engineers implementing the products don't understand the context they are designing for. While there are exceptions, this is the general trend. We believe the research presented here addresses the root

causes of failure and lack of impact for developing world products. This work has been rigorously analyzed so as to be generally applicable and useful to other engineers and not simply anecdotal. While it is not highly technical, it is the start of identifying the parts that are missing from engineering literature and practice in this area of design.

Each chapter in this dissertation represents the synthesis of general principles and insights from a different source of experiential knowledge:

1. The archival engineering literature [42]
2. The experiences of practitioners working in a non-profit setting [43], [45]
3. Our own experiences as researchers in four different countries on four different continents [46]

Chapter 2 is a review of the engineering literature related to design for the developing world. Chapters 3 and 4 come from the experiences of practitioners. In chapter 3, this experience was shared in the form of published Failure Reports from Engineers Without Borders Canada and other field reports describing the implementation of products in developing communities. In chapter 4, this experience was gleaned through personal interviews with the founder of an organization, WHOLives.org, that alleviates poverty by increasing access to clean water through a product called the Village Drill. Chapter 5 describes our own experiences using ethnographic techniques to collect customer needs under a variety of conditions in four countries on four different continents.

What each of these chapters have in common is the process we used to derive general principles and insights. In each piece of this research, we took a large set of information, then categorized, filtered, and analyzed it until general principles and insights emerged, and finally reported on those general principles and insights. The sources of the information we analyzed were varied in an attempt to establish principles and insights from various sources of experiential knowledge.

We define a design principle as a fundamental proposition used to guide the design process. The principles discussed here are not suggestions or activities the designer should complete, they are assertions that can guide the designer to a more effective outcome. The principles do not explicitly say what should be done; they simply guide the engineer as decisions are made. They

may not be exclusive to the developing world, but the literature, experiences of practitioners, and our own experiences suggest that it is extremely valuable to consider them and that their application is different in subtle ways from their application in the developed world. Although principles are not guaranteed, and at times they should not be followed, they should always be considered [47].

1.3 Principles from the Engineering Literature

Chapter 2 of this dissertation is a review of the engineering literature related to design for the developing world. In this chapter, we examined 232 sources including journal articles, conference papers, textbooks, books, and technical reports. From each source, we listed the key insights reported by the authors and then combined similar insights into groups. Using the KJ Method [48], we iterated through these categorizations several times and in the end, nine main trends emerged. These trends were articulated as principles that can be used to guide other engineers as they design for the developing world. The nine principles are:

1. Co-design with people from the specific developing world context encourages designer empathy, promotes user ownership, and empowers resource-poor individuals
2. Testing the product in the actual setting is an essential part of design for the developing world, not merely a final step
3. Importing technology without adapting it to the specific developing world context is ineffective and unsustainable
4. Both individuals in urban and rural contexts can benefit from poverty alleviation efforts
5. Women and children are more affected by poverty alleviation efforts than men
6. Project management techniques that are adapted to the specific developing world context enable a more effective and efficient design process
7. Products for the developing world have greater impact when contextualized, developed, and implemented by interdisciplinary teams.
8. Cooperation with governments and local influencers contextualizes and enables poverty alleviation plans

9. There are existing distribution strategies that can be used to successfully introduce products into developing world markets

After each principle is articulated, we describe the literature that supports the principle, give a more detailed example of that principle from the literature, and provide suggestions for using the principle in day-to-day engineering practice.

We then compare the nine principles to other, more general design principles. This comparison shows that, while these nine principles are pertinent to product development, they are not related directly to the basic solution finding process which consists of four steps; (1) requirement establishment, (2) solution generation, (3) solution evaluation and selection, and (4) solution embodiment. Rather, they have to do with the context surrounding product design decisions and with the teams that make those decisions.

This idea of context is one that surfaces again in each of the other chapters. The context is the set of circumstances that form the setting for the solution. It is important to recognize that requirements and context are not the same thing. To solidify this idea, consider this context (or circumstance that forms the setting): Many people in Burundi earn less than \$271 annually. This context informs – but is not itself – a requirement. The informed requirement for a disposable medical device, for example, could be that it costs less than \$0.05 for an impoverished Burundian to purchase. This requirement is informed by the low-income context.

On one hand, it is surprising to find very few principles in the literature that guide the engineer to understand the context for *developed world* products. On the other hand, this is not surprising since the engineer has typically lived his or her entire life in the developed world context and can relate to it naturally and intuitively. Creating products for the developing world, however, requires the engineer to understand and design for a context that is not at all natural to him or her. This understanding of the context seems to be a key factor that determines the impact design teams can have.

1.4 Insight from Practitioners

In Chapter 3 of this dissertation, we present pitfalls common for the implementation of products in the developing world, as well as a tool for overcoming them. These pitfalls came

mostly from practitioners working in a non-profit setting as well as from our own experiences in an academic setting.

In 2008, Engineers Without Borders (EWB) Canada published their first Failure Report [49]. The purpose of this report was to share past failures with the goal that these failures not be repeated by other engineers. After a positive response from the engineering community, it was decided that a similar report would be published each year. These reports document the experiences of practitioners working in the field on developing world projects. Most of these practitioners were hired as fellows and spent 12 to 20 months working in the field. We chose to study these reports from EWB Canada because, unlike projects often published in academic journals, these reports focus specifically on the challenges encountered and the mistakes made rather than highlighting the positive outcomes of the project.

We were careful to choose only the reports that had to do with implementing a physical product and did not use reports that were related to mistakes made running a Non-Governmental Organization (NGO), leading a student chapter of EWB Canada, or other related activities such as advocacy or fundraising. Of the 72 reports published between 2008 and 2014, 27 were about implementing physical products. We also included 14 field reports for developing world projects completed between 2011 and 2014 by members of our own research group, for a total of 41 field reports examined.

For each field report, we extracted statements that represented the failure modes for that project. As often as possible, these statements were taken verbatim. For all projects combined, this generated a list of 225 statements. Redundant statements within a given project were then combined, reducing the total number of statements to 142.

These 142 qualitative statements were then organized into themes using the KJ Method, which was developed to help reveal themes in ethnographic data from Nepal and often results in an affinity diagram [48]. This was done by a group of four researchers with experience in design for the developing world. Ultimately, seven distinct themes emerged and each of these themes is articulated as a pitfall. The seven pitfalls do not encompass *all* of the pitfalls an engineer may face in designing for the developing world; these are only the pitfalls found in this rare and valuable data set. The seven pitfalls are:

1. Lacking the contextual knowledge needed for significant impact

2. Neglecting to make a plan for or developing partners for long-term sustainability
3. Assuming the needs of the customers being served
4. Not making a plan for or developing partners for manufacturing
5. Lacking skills or expertise for a specific project
6. Miscommunicating or failing to develop trust with local stakeholders
7. Forgetting that communities change over time between field visits

In Chapter 3, each of the pitfalls is described in greater detail. A tool called the Design for the Developing World (DFDW) Canvas is introduced to help engineers overcome these pitfalls. This canvas is akin to the Business Model Canvas [50] in that it is a visual tool, but instead of helping a team develop a business model, the DFDW Canvas helps a team navigate the product development process in a way that helps them consciously avoid these pitfalls. The DFDW Canvas contains six parts: Customer, Product, Impact, Delivery, Manufacturing, and Revenue Model. The team should consider the contextual factors and community partners as they discuss each of the six parts. The sections of the DFDW Canvas are not linked explicitly to the pitfalls; they are linked explicitly to aspects of the product design process, allowing it to naturally complement the other design activities the team is already doing. The DFDW Canvas can also be used after a project is completed to evaluate the project. Later in the chapter, a case study using the DFDW Canvas is described. In this case study, the DFDW Canvas is used in the implementation of a pot skirt in rural Northern Peru [51]. This pot skirt is a product that surrounds the pot and increases the efficiency of combustion and heat transfer while still using the traditional cookstove. This allows the user the benefits of an improved cookstove without having to change their traditional cooking style or fuel, thus increasing adoption rates.

1.5 Case Study from a Non-Governmental Organization

The fourth chapter of this dissertation is an in-depth case study of one product, the Village Drill, and the organization that supports it, WHOlives.org. The Village Drill is a human powered machine that creates boreholes for water wells and is designed to reach water up to 76 meters (250

ft) below the surface. This provides both a low-cost alternative to traditional drilling systems and a highly effective alternative to older, low-cost but labor-intensive drilling techniques like auguring and sludging. Once a borehole is drilled and water has been accessed, the borehole is cased and a hand pump makes water available to members of the community. The Village Drill belongs to WHOlives.org – a non-profit organization that commissioned Brigham Young University (BYU) to design and test the Village Drill.

The case study follows the six sections of the DFDW Canvas, described in Chapter 3: Product, Customer, Impact, Manufacturing, Delivery, and Revenue Model. It describes in detail the events of the first five years of the organization including field trips, cash flows, and changes to the design and manufacturing. This is very uncommon for design for the developing world literature, which typically includes reports after only the initial implementation of a product. The longer time scale of the information presented here provides greater insight into the resources required to have a positive impact in such an uncertain context. For this case study, WHOlives.org was willing to disclose their actual data about how much things cost, the price and number of drills sold, and other details that are not commonly found so openly shared in the literature. This allowed us to present an unobscured and unembellished description of this product and its impact.

The further engineering development of the Village Drill is described, as are the manufacturing partners, and the strategy development of WHOlives.org. An impact model for the Village Drill including a sensitivity analysis is also provided in the chapter. The model estimates with 97.6% confidence that the Village Drill has provided over 170,000 people with 2 million people-months of water since its initial implementation. In the first five years, it has produced over 1000 boreholes, 761 of which have lead to water, and employed 238 people for a total of 5,838 months of employment.

1.6 Insights from Our Field Studies

Chapter 5 is a collection of insights from the analysis of our own experiences collecting customer needs and feedback in developing communities in four countries on four different continents. For these field studies, we worked with social scientists to experiment with the use of *ethnography* for collecting customer needs in developing communities. The word *ethnography* has different meaning in different disciplines [52]. Traditional ethnography in the social sciences is the

study of other cultures, contexts, and people in their natural settings [53] as they go about their everyday lives [54]. Nevertheless, a fundamental purpose of ethnography is to help the ethnographer understand context and culture, whether that culture is as narrow as a profession (e.g. surgeon) or as broad as a geographic region (e.g. Southeast Asia).

The principles of ethnography have been used by product design engineers to build empathy, understand customers and their contexts [55], and learn about needs for a product [56]. When used in this way, these activities are referred to in the literature as *design ethnography*. Design ethnography is focused on collecting information about problem-specific context and needs [55] whereas traditional ethnography is focused on the broader purpose of understanding culture and context in a holistic way [57]. Design ethnography is often completed more quickly (hours or weeks) than traditional ethnography (weeks or years). Some researchers and practitioners have developed frameworks for completing design ethnographies [58]–[62], but very few have quantified any aspect of the process.

In Chapter 5, we focus on quantifying aspects of ethnography for a specific subset of design ethnography called *cross-border design ethnography*. Cross-border design ethnography is design ethnography completed across national borders where differences in language and culture can strongly influence the effectiveness of the design ethnography. The aspects quantified in this study include the influences of cultural familiarity, language fluency, ethnographic activity used, information source type, gender and age of the respondent, use of prototypes during ethnographic activities, and the type of need statements collected on the ability of the design team to collect information that is useful in making product design decisions.

The results of this paper are particularly useful when designers from developed communities are designing products for customers in developing communities because designers are unfamiliar with the context. As a result, their intuition is less reliable for making design decisions about products used in these communities [63], [64]. When information is scarce, engineers often make assumptions to fill in gaps in their understanding of customer needs. In situations that are not intuitive to the designer, these assumptions are often incorrect, leading to the design of products that do not as effectively alleviate poverty.

The four countries visited were Brazil, India, Rwanda, and Spain. A total of 264 ethnographic activities were conducted, resulting in 6,050 pieces of information that were analyzed using

six descriptors and 18 codes with a total of 22,735 code applications. After the coding, statistical analyses were performed which allow us to draw quantitative conclusions about how the different conditions in each field study affected the teams' ability to collect information that is useful for making product design decisions. These conclusions are listed as odds ratios, which indicate the likelihood of collecting useful information in one condition compared to another.

Some of the results we found were intuitive and some were not, but all can be used by design teams to plan more effective cross-border ethnographic studies. The results indicate that language fluency has a more significant impact than cultural familiarity and that, for problem-area focused ethnographies, having cultural familiarity, language fluency, and community partners makes the design team significantly more likely to collect useful information for product design decisions than if any of the three are missing. In situations where the design team is conducting a more open-ended ethnography, the results show that having community partners only is the condition most likely to give useful information because it is the condition that requires a translator who can filter out the information that is less useful for product design. The results also show that generally, the design team will get the most highly useful information from female respondents, middle aged respondents, primary sources, and explicitly stated needs – though a variety in each of these categories is important for a well-rounded study – and that the use of prototypes has a surprisingly large impact on the collection of useful information.

1.7 A Note on Terminology

When this work began several years ago, the research community was so young that it didn't have one distinct name. Even now, the work of designing products for people that live in developing communities with the goal of alleviating poverty has many names. Unlike other well-defined areas of research where literature is easily accessed through specific journals or by searching specific phrases, this research is spread across many different journals and is known by such names as appropriate technology, design for resource-poor environments, design for resource-poor individuals, humanitarian engineering, global engineering, engineering for change, and design in less industrialized economies. The literature also includes a high proportion of student projects. Each university that has a program for these kinds of projects seems to also have its own name for

them, such as service learning, Engineers Without Borders projects, global engineering outreach, and others.

In the last couple of years, two names for this research seem to have emerged as the most commonly found in the literature: (i) design for the developing world, and (ii) engineering for global development. While both are valid and useful, we have chosen to use the former in this dissertation for several reasons. First, to be consistent with the language of the work that we and others have previously published. Second, to be consistent with other “Design for X” literature. Third, because while the distinction between *design* and *engineering* is subtle and debatable, it is particularly significant for this type of product development. As mentioned earlier, the majority of products for the developing world fail because the people creating them lack an understanding of the context. While *engineering* often focuses more on the technical side of the product being developed, *design* often focuses more on the person who will eventually use that product. This human-centeredness is essential to designing products that will successfully alleviate poverty. The softer skills of having empathy, understanding customer needs, and considering the context of use are more needed in situations when the designer’s intuition is not as reliable. In speaking of these softer skills, George and Shams point out that “engineers don’t have this training!” [65].

As we’ve studied the literature and through our own field studies, we’ve seen that every engineering project for the developing world needs three things:

1. An accurate understanding of the customer needs
2. A product that is well designed and/or engineered
3. A sustainable distribution system or business plan

When each of these three parts is done well, the product has a much higher chance of success. Sound engineering is essential to the success of the second item; obviously, the product has to do what it was intended to do safely and affordably. But sound engineering alone will not create widespread impact. Design encompasses a broader range of skills that are essential to the first and third items. The phrase “design for the developing world” emphasizes the role design has to play in poverty-alleviating products and thus, has been used throughout this dissertation.

CHAPTER 2. NINE PRINCIPLES FOR DESIGN FOR THE DEVELOPING WORLD AS DERIVED FROM THE ENGINEERING LITERATURE

2.1 Chapter Overview

This chapter reviews the findings of several engineering researchers and practitioners on the topic of design for the developing world. We arrange these findings into nine guiding principles aimed at helping those who are searching for effective approaches for design for the developing world. The findings reviewed come from the mechanical engineering discipline, as well as from other engineering and non-engineering disciplines. For each principle, we provide references to various studies as a means of supporting the principle. We also provide a detailed example of each principle. Based on our own experience and based on the many papers reviewed, we provide a succinct list of suggestions for using each principle. Finally, we relate these nine principles to traditional design principles. Ultimately, we believe that the principles introduced here help overcome the challenges of design for the developing world, which are often dominated by designer unfamiliarity with poverty and foreign culture and the constraint of extreme affordability.

2.2 Introduction

Twenty percent of the world's population lives on less than \$1.25 a day [1]; a stark contrast can be made to the average mechanical engineer in the United States, who earns enough to live on \$283.55 a day [66]. These resource-poor individuals face significant life challenges including lack of clean drinking water [67]–[76], chronic hunger [38], [77], [78], inadequate health care [79]–[81], short life expectancy [82], inadequate housing [83], poor education [84]–[86], and lack of sanitation [87], [88], [88]–[90]. There is no shortage of want for these basic needs, and there is no shortage of opportunity to deliver as resource-poor individuals, which includes the individuals making less than \$1.25 a day, represent a \$5 trillion market [5]. Many have observed and reported on the tremendous opportunity for business in these markets [6]–[16]. There is a shortage how-

ever in our understanding of how to effectively serve this market in a way that produces a lasting impact; many decades of effort has gone into trying with varying degrees of success. This chapter reviews a portion of that work and articulates principles from the recurring themes, experiences, and conclusions of many different people.

In the past decade, there has been a surge of effort to reach resource-poor markets from leaders in business, social science, international development, and engineering. Most prominent in the engineering literature is the work carried out by electrical and civil engineers to design and install electrical, water, and sanitation systems for resource-poor *communities* [20]–[27]. In contrast, very little work has been published in the area of product design for resource-poor *individuals* [28]–[31]. Considering the life challenges listed above, innovative products have the potential to make a significant impact. The term *product* is used in this dissertation to describe any consumer good that is purchased by an individual or household. This includes medical products, income-generating products, mobile communication products, educational products, or any other products that make life easier or more enjoyable for the purchaser in some way. While mechanical engineering is not the only professional field with training in product design, mechanical engineers are well-trained in mechanical design, optimization, and manufacturing techniques – all of which may be needed to produce effective product solutions. Unfortunately, the opportunity and urgency to find solutions that alleviate poverty are far greater than the number of mechanical engineers currently involved.

There is a small subset of mechanical engineers who focus their research and professional efforts on alleviating poverty and their contributions have been valuable [30], [38], [40], [65], [68], [71], [91]–[99]. But greater impact is needed. Over the past decade, interest in design for resource-poor individuals has grown among students and professionals [17]. Engineers Without Borders membership in the US, for example, increased 500% between 2005 and 2011 [18] and the Editor-in-Chief at ASME Magazine describes product design for the developing world as an area of research “worth pursuing” in 2011 [19]. Unfortunately, a generalized set of guiding principles to support these growing engineering interests is absent from the literature and common practice.

In this chapter, we review the findings of several engineering researchers and practitioners on the topic of design for the developing world. We arrange these findings into nine guiding principles aimed at helping those who are searching for effective approaches for design for the

developing world. We also provide a critique of the nine guiding principles and describe how they relate to traditional design principles.

We define a design principle as a fundamental proposition used to guide the design process. The principles in this chapter are not suggestions or activities the designer should complete, they are assertions that can guide the designer to a more effective outcome. The principles do not explicitly say what should be done; they simply guide the engineer as decisions are made. They are not exclusive to the developing world, but the literature suggests that it is extremely valuable to consider them and that their application is different in subtle ways than their application in the developed world. Although principles are not guaranteed, and at times they should not be followed, they should always be considered [47].

For each principle, we provide reference to various studies as a means of supporting the principle. We also provide a detailed example of each principle. Finally, based on our own experience and based on the many papers reviewed, we provide a succinct list of suggestions for using each principle.

2.3 Nine Principles for Effective Design for the Developing World

In this section, we articulate and support principles related to design for the developing world – as derived from the engineering literature. We also provide illustrative examples and suggestions for how each principle can affect the day-to-day engineering of those involved in designing products for individuals in the developing world. The nine principles described in this section are:

1. Co-design with people from the specific developing world context encourages designer empathy, promotes user ownership, and empowers resource-poor individuals.
2. Testing the product in the actual setting is an essential part of design for the developing world, not merely a final step.
3. Importing technology without adapting it to the specific developing world context is ineffective and unsustainable.
4. Both individuals in urban and rural contexts can benefit from poverty alleviation efforts.

5. Women and children are more affected by poverty alleviation efforts than men.
6. Project management techniques that are adapted to the specific developing world context enable a more effective and efficient design process.
7. Products for the developing world have greater impact when contextualized, developed, and implemented by interdisciplinary teams.
8. Cooperation with governments and local influencers contextualizes and enables poverty alleviation plans.
9. There are existing distribution strategies that can be used to successfully introduce products into developing world markets.

Notice that each principle is fundamentally centered on the problem and solution context, where the context represents the circumstances that form the setting for the problem and/or solution. Importantly, we note that only when the context is established and understood can the solution finding process produce a valuable outcome. In other words, without an understanding of the context, it is impossible to know if a given solution can or should be implemented.

The remainder of this section is organized such that each subsection is dedicated to a single principle. In each of these subsections the following is given; (i) a brief articulation of the principle, (ii) a summary of the supporting literature, (iii) an example from the literature, and (iv) suggestions for using the principle.

2.3.1 Principle 1: Co-design with people from the specific developing world context encourages designer empathy, promotes user ownership, and empowers resource-poor individuals.

Articulation

Co-design is the act of collaborative and egalitarian product development with resource-poor individuals. It (i) expands the designer's understanding of the needs of resource-poor individuals, (ii) expands the designer's understanding of the setting/environment where the products will

operate, (iii) promotes design ownership (or the feeling that the idea or object belongs to the individual) among resource-poor individuals, and (iv) empowers them for current and future product development activities.

Support

Based on their experience gained through the co-design of toilet systems for Indian slums, Burra et al. [89] state that designing collaboratively with the community for which the product is intended leads to more impactful products. They point to resource-poor individuals as invaluable experts; these individuals know what their problems are and they know which solutions they prefer. Burra et al. observed such expertise when local users of the toilets helped design and build them. A lasting impact was achieved for the toilets because there was a strong sense of ownership for them among the resource-poor individuals. This ownership is evidenced by their willingness to pay a monthly fee so community members can be compensated to maintain the toilets. This ownership is due in part to their participation in the design process.

Co-design can be implemented to varying degrees. Nieuwma and Riley [100] teach that simply talking to people in low-resource communities is only the beginning. In order for them to be truly committed to and excited about the resulting product, designers must involve resource-poor individuals in the concept generation, concept selection, and other important phases of product development [47], [101]–[104].

Nieuwma and Riley [100] use two case studies to describe that even when working with people from a developing country we must choose the right people within that country to work with. They most often worked with people from Non-Governmental Organizations (NGOs) and universities, and found that these people rarely lived in poverty themselves and therefore didn't fully understand the challenges of poverty. This type of co-design approximates but does not fully embody the four hallmarks of co-design articulated by Murcott below [93].

Hallmark 1: The co-design partnership is egalitarian and synergistic. Hallmark 2: Recognition that resource-poor individuals have valuable expertise in surviving in low resource environments and in understanding local materials and networks. Hallmark 3: The co-design test lab is the actual environment where the final product is intended for use. Hallmark 4: The ultimate degree of co-design occurs when the collaboration is expanded widely, for example under the framework of open-source innovation [105].

To have a more useful engagement with the stakeholders of their designs, Cruickshank and Fenner [106] believe that engineers need to “evolve and embrace some of the ‘soft skills’ that lie at the interface of the physical sciences and the humanities/social sciences.” George and Shams [65] also suggest this. Nieuwma and Riley [100] observe that because engineers have a tendency to focus too heavily on technology, they can sometimes forget about other factors that significantly affect the impact of their work, such as social power relations, governmental constraints, and project sustainability. Novy-Hildesley [107] suggests that if engineers had more training in business, the impact of projects would be improved.

Witherspoon and Harris [108] say that we need to listen to what resource-poor individuals in the community actually want and need in order to be effective. Two other publications, not reviewed here, illustrate the value of this principle in the area of women’s healthcare in developing countries [109], [110]. There are also other publications that support the principle of co-design [96], [111]–[115].

Example

As a more in-depth example of this principle, let us consider more fully the toilet system described by Burra et al. [89]. Urbanization in India has presented many unique challenges. In some cities, as much as 50% of the population lives in informal slum housing with inadequate sanitation. The sanitation improvements the government undertook were infrequent, slow, expensive, and were designed without consulting people living in the slums which made the improvements ineffective. Burra et al. worked with women’s cooperatives, an Indian NGO, and many government leaders to build toilet systems for over half a million resource-poor individuals in eight Indian cities. The strategic use of co-design led Burra et al. to this effective and impactful solution.

In an effort to protect their modesty, women in Indian slums often wait until dark to defecate which can cause gastric disorders and children are often pushed out of lines for the small number of available toilets by men. Because of this, women and children have the most to gain from improved sanitation. Burra et al. focused much of their efforts on the needs of women as they designed new toilet systems for these communities. After extensive surveys and interviews with people (mostly women) who use these toilets, they found that the most important features to the resource-poor community members were (i) that the men’s and women’s toilets be separate, (ii) that there be a water tank to ensure adequate water supply for hand washing stations and for cleaning the toilets,

and (iii) that they would be built as inexpensively as possible to ensure that the largest number of people could be served. Interestingly, these features were not included in the government's previous designs. Furthermore, as the co-design efforts initiated by Burra et al. continued, many other innovative changes were added to the toilet design.

Throughout the process of designing and building, weekly meetings with community leaders, NGO workers, and government officials were held. According to Burra et al., this provided a channel for open communication, encouraged government officials to respect these previously marginalized community members, and decreased the occurrence of bribes and corruption during the construction phase. These interactions also gave female leaders confidence in their abilities and empowered them to make changes in their own communities. Women with no previous construction experience and little education began bidding for contracts to build the toilets and even began training women in other communities to do the same.

Suggestions for using this Principle

1. Respect the potential for resource-poor individuals to make significant design contributions.
2. Immerse yourself in the culture of those for whom the product is intended. Optimally, travel to the intended setting and interact with them. Otherwise bring as much of the local setting to your current location as possible. Use personas (a representative profile to describe user behavior [116]), or locales (same concept as personas but the focus is a location, not an individual).
3. Invite resource-poor individuals to join the design team; ensure that they are compensated for their effort; ensure that they have an appropriate and meaningful way to participate.
4. Consider the complete product life cycle. This will require the design team to consider more fully the product's long-term integration into the intended setting, which includes defining the supply and distribution chains. Such considerations are facilitated through co-design.

2.3.2 Principle 2: Testing the product in the actual setting is an essential part of design for the developing world, not merely a final step.

Articulation

Comprehensive simulation environments are not possible to create in a laboratory setting. The complexities of the physics, coupled with political, social, and cultural influences are simply beyond our ability to simulate at high fidelity. As comprehensive testing is a part of effective product development, we must include field testing in the actual setting as part of the evolutionary process, not merely as a final validation of the concept.

Support

Bailis et al. [117] stress the importance of different validation tests at different stages of product development and implementation. Their experience in the area of biomass cookstoves illustrates that although product development teams can have good results in the lab, the actual product impact is not usually measured. To begin such a measurement, teams could ask: (i) Does the product perform the same in the field as in our lab? (ii) Do the people who own the product actually use it? (iii) Do they use it the way we intended for them to use it? (iv) Have we done enough follow-up research to answer these questions?

As the number of engineering projects for the developing world increases, it is important for us to establish a method for evaluating the quality of the projects. Scott [118] provides a manual for project evaluation and George and Shams [65] introduce three questions that could be used to evaluate a design team's product; (i) Have the customer needs been met? (ii) Is the project sustainable and maintainable by the customer? (iii) Does the project respect the environment and make effective use of local renewable resources? Clearly, the value of mid-development field testing is indispensable in answering these questions.

Murcott [93] proposes a pattern for effective design for the developing world, which includes the recognition that field testing outweighs all laboratory simulations. Importantly, Harris and Marks [119] emphasize that carefully choosing the test/implementation site is critical to the product's success. For their work in the area of perinatal ultrasound, some key factors are the size of the client base, transportation to the clinic, availability of trained staff members, security of the

equipment, and import/customs laws. Undoubtedly, attempts to fully simulate these factors in a laboratory setting are ineffective compared to field testing.

Candid discussions of successes and failures that support this principle are provided in [49], [79], [89], [120]–[127].

Example

Ngai et al. [128] experienced the value of this principle as they worked on water filtration in Nepal. Arsenic and pathogen contamination are common in the well systems used by 90% of the southern Nepalese population. Arsenic contamination is as much as 100 times the recommended limit, and microbial contamination is the single largest cause of waterborne disease and death. Ngai et al. developed a filter to solve these problems and used the principle of field testing to achieve results with lasting impact. They started with clear goals for the filter related to ease of use for women and children, being low cost, and having a certain minimum flow rate. After a survey of existing technologies, 50 potential solutions were identified and 8 were thought to be viable in rural Nepal. These 8 were tested in a laboratory setting and the best 3 were chosen. Then, a total of 180 filters of these 3 types were distributed to households in Nepal and monitored monthly for 4 to 12 months. The technical, social, and economic performances of the filters were rigorously tested to determine which filter would provide the best solution for the target communities. After it was established that the Kanchan Arsenic Filter [128] was the best, Ngai et al. prepared the filter for local manufacturing in Nepal. One year later, over 80% of households were still using the filter daily and four years later, over 500 filters were in operation. The emphasis the team placed on testing – not just in the laboratory, but also in the field – was essential to the filter’s impact.

Suggestions for using this Principle

1. Answer the questions posed by Bailis et al. [117]. Do we have enough information to understand if people are using the product the way we intended with the same results found in the lab?
2. Answer the questions posed by George and Shams [65]. Does the product meet the customer’s needs while being maintainable and respecting the environment and local resources?
3. Allocate financial and time resources for field testing.

4. Choose implementation and/or test sites carefully.
5. Plan for field testing to be a mid-development activity, not a post-development activity.

2.3.3 Principle 3: Importing technology without adapting it to the specific developing world context is ineffective and unsustainable.

Articulation

Technologies that have been successfully integrated into the developed world will not generally integrate into the developing world effectively or sustainably without first being adapted.

Support

Subrahmanyam and Gomez-Arias, [5] emphasize that to enter low-resource markets it is not effective to simply remove features to make products less expensive, but it is effective and necessary to adapt and tailor products to be more relevant to the various needs of resource-poor individuals. In their efforts to design ultrasound devices for perinatal care, Harris and Marks [119] say that finding the balance between introducing new technology and respecting tradition is difficult. They also indicate that training models must be tailored to the new setting and personnel.

In Nieuwma's studies [33], he points out that imported technology did not yield the desired results because the context of the technology's development and use were very different. Nieuwma and Riley [100] also say it's a difficult task to design something that works well for people in low-resource settings. Further, it is hard for engineers from developed countries to let go of their assumptions and focus on doing what is right for the resource-poor market.

Donaldson [129], however, conducted a study of local products and design activities in the formal, informal, and non-governmental sectors in Kenya. She reports that products produced in Kenya fell into one of four categories: (i) imitation of foreign-designed products, (ii) imported designs, (iii) original basic design, and (iv) specialty design. Of the 55 products traced to the manufacturer, 54 were based on foreign designs – and therefore, were imported to some degree. She then explores the opportunities and constraints that encourage or discourage local design in developing countries.

After designing and attempting to establish local manufacturing for a manual mechanical shredder, Weiss et al. [130] made observations that support this principle. They observed that

manufacturers in the developing world prefer to operate based on locally proven, established approaches instead of on less familiar, less certain approaches, even when those approaches have been highly effective in the developed world. This was due, in part, to the difficult challenge of overcoming cultural norms, such as those related to the concepts and expectations of production quality control.

A different yet equally interesting phenomena in the developing world was encountered by Wijayatunga and Attalage [131] as they analyzed the use of electricity in rural Sri Lanka. They observed that using existing technology to reduce the effects of poverty can actually create unanticipated use-scenarios and demands for that technology – even a new use-scenario that does not reduce the effects of poverty. In the area of rural electrification, various researchers express concerns in support of this principle [84], [122], [132], [133].

Other support from Akubue [34] indicates that importing large-scale technologies from the developed world does not generally help alleviate poverty in the developing world because these technologies are capital-intensive in a market with little capital. Further, costly labor-saving technologies are not valued in communities with excess labor capacity. Ultimately, according to Akubue, the importation of large-scale technologies encourages urbanization and can help resource-poor individuals in urban settings, but it creates a larger income gap between the rural and urban communities.

Alder et al. [79] share their experience with this principle. They travelled to the community and spent most of their time and effort training people to use the new technology. Community members also tracked their use of the new technology so Alder et al. could evaluate the effectiveness of importing it. It was generally successful, but the training had to be modified significantly to be appropriate for the needs of resource-poor individuals in that area. Witherspoon and Harris [108] offer several suggestions for evaluating the usefulness of a technology in a resource-poor community and provide questions that help designers challenge their own assumptions and make design decisions that are more effective for the intended users of the technology.

There are also examples of individuals, companies, and other organizations importing technology sustainably but these examples are not commonly found in the engineering literature and thus have not been reviewed here. Examples include mobile phones and plastic containers, which are ubiquitous in the developing world. Perhaps these have become ubiquitous because the tech-

nology itself is already adapted to the developing world. For example, mobile phone infrastructure costs are about 40% of the cost of building a landline network [134], and is therefore an appropriate choice for the developing world.

Example

Wijayatunga and Attalage [131] experienced the realities of this principle as they studied barriers to adopting clean and convenient energy sources. In many developing communities, the goal of electrification is to reduce the amount of biomass used in cookstoves so as to decrease harmful emissions and slow the rate of deforestation. Through their study of domestic energy sources in Sri Lanka, they found that the electrification of a community did not decrease the amount of biomass used for cooking. Because biomass could be gathered and did not have to be paid for, members of the community chose to use the electricity for things that only electricity could be used for such as lightbulbs, radios, and televisions. They continued to use biomass to cook because they were accustomed to working with it and preferred the way their food is prepared using that fuel. Instead of replacing other sources of energy as anticipated, electrification increased household demand for energy by providing access to new technologies. The electrification of this community had many benefits, but as far as reaching the goals of decreasing dangerous emissions and reducing deforestation, the importation of this new technology was ineffective.

Suggestions for using this Principle

1. Examine the various unanticipated use-scenarios for new technologies using tools such as Failure Modes and Effects Analysis [104].
2. Understand the social context as well as possible ways to avoid implementing existing technology that will not integrate well in the developing world.
3. Use robust design techniques [135] to develop products that will operate well without having to be produced with small tolerances.

2.3.4 Principle 4: Both individuals in urban and rural contexts can benefit from poverty alleviation efforts.

Articulation

Resource-poor individuals in *rural* settings have been the focus of significant poverty alleviation efforts [22], [38], [40], [77], [96], [110], [136]. Resource-poor individuals in *urban* settings, however, also benefit from poverty alleviation efforts.

Support

Fisher [38] states in 2006 that 70% of people living on less than \$1 a day are rural subsistence farmers. Because of this, efforts have focused on pumps and irrigation systems to help these farmers increase their income by helping them to grow more crops.

But in the last decade these resource-poor farmers have been increasingly moving to urban areas where they are met with inadequate housing, a lack of sanitation and access to water, and unemployment. The United Nations (UN) [137] reports that there are over 1 billion people living in urban slums and that this number is expected to double by 2030. Cruickshank and Fenner [106] state that 19 out of 26 cities with populations over 10 million are in the developing world, as are 40 of the 61 cities with populations over 5 million. These numbers are only expected to increase. Cities with large populations living in slums are spread across South America, Africa, and many Asian countries, most notably in India where often half of the urban population lives in slums [89].

The scale and urgency of the problems faced by those living in urban poverty are overwhelming, but this new trend of urbanization offers some advantages. Programs that provide essential services like sanitation, healthcare, and employment opportunities can be more easily implemented in these densely populated areas. Products can be more easily marketed and distributed in this setting as well. Many slum communities have their own social organization and are generating innovative solutions to the problems that their communities face. With proper support from designers and engineers, solutions to their challenges are attainable [89].

Example

Morawczynski and Miscione [138] discuss the effects of mobile phone enabled banking on resource-poor individuals living in urban settings. More than 60% of the population in Nairobi, Kenya lives in one of Africa's largest slums, an area called Kibera. Only 17% of adults in this area

are permanently employed and HIV rates are 4 times larger than Kenya's national average. People living here lack access to employment, water, sanitation, electricity, and many other services, including banking. Traditional banks are available in Nairobi, but resource-poor individuals can not usually afford the monthly fees and traditional banks are hesitant to open in Kibera because of security issues.

In March 2007, Safaricom introduced a banking service called M-PESA that allows resource-poor individuals to make deposits, withdrawals, transfers of money or phone credit, and even pay for goods at stores using their mobile phones. The majority of customers living in Kibera use this service to send money to family and friends in rural areas. Customers go to an M-PESA agent to deposit or collect their money, then receive an SMS message to their mobile phone confirming the transaction. After visiting several agents in the area, Morawczynski and Miscione decided to study the busiest agent in more depth. They observed her transactions and interviewed her and her customers. They learned that there are approximately 50 to 65 transactions per agent per day. There were typically more deposits than withdrawals, showing that resource-poor individuals are mostly using this service for remittances or to save their money. The agents reported that people would typically deposit large sums of money and then make small withdrawals throughout the month.

After one year, there were almost 2 million registered M-PESA customers in Kibera and this number has continued to grow; the program was able to spread quickly because of the dense population in the urban setting. For some customers, this was their first exposure to the formal economy. This service was successful in Kibera because it was tailored to the needs of resource-poor individuals in this urban area.

Suggestions for using this Principle

1. Consider the opportunities that exist in both urban and rural settings for poverty alleviating products.
2. Understand the unique conditions of both urban and rural settings and how they should influence the design.
3. Thoughtfully choose to design the product for urban, rural, or both settings in order to have the greatest impact.

4. Consider how the product will be purchased by and delivered to the customer in the chosen setting.

2.3.5 Principle 5: Women and children are more affected by poverty alleviation efforts than men.

Articulation

Women and children are typically more vulnerable to the challenges of poverty than men and are therefore more affected by solutions to those challenges. Also, women are most often the ones who will bear the ongoing labor burden associated with poverty alleviating products.

Support

Burra et al. [89] explain that women and children in Indian slums are most severely affected by a lack of sanitation. Women are busy cooking in the mornings and cannot accompany their children to wait in line for toilets, so children are often pushed out of the way by adult men. The government-built toilet systems had no separation for women and men, so women had little privacy and were often harassed as they used the toilets. Because of this, women and children benefited most from the improved toilet design.

Murcott [93] explains that we should use engineering to create freedom from disease, poverty, and environmental degradation. She points out that “women and children are usually the most vulnerable and severely affected” by these kinds of problems. She also says that we should use engineering to create education, dignified work, and safety.

Women are often the key figure in establishing lasting solutions because they typically manage household resources. In many cases, if a solution is going to be successfully implemented, it will need to be accepted by the women. Biswas et al. [22] say that “women play a vital role in both cooking and energy management,” and Ngai et al. [93] report that one of the criteria for their water filter was that it be acceptable to the women, since they are the typical managers of household water. Because of women’s direct role in implementation, they are strongly affected by efforts to alleviate poverty – especially because women are most often the ones who will bear the ongoing labor burden associated with poverty alleviating products [77].

Women also face many challenges that men do not, the most obvious of which is bearing children. Harris and Marks indicate that maternal mortality is the leading cause of death for women of child-bearing age in developing countries [119]. Additionally, the responsibility of bearing and raising children prevents women from being employed outside the home, which leaves women (most certainly single mothers) vulnerable to poverty in more ways than men.

Example

Harris and Marks [119] embraced this important principle when they learned that maternal and infant mortality rates were significantly higher in developing countries – an issue that only directly affects women and children. Their solution to this problem was to select and implement a compact ultrasound device that would operate well in a low-resource setting. The selected compact ultrasound device was sturdy, designed to work with rechargeable batteries where electricity was not available or reliable, and was portable enough to be used in many situations, such as at bedsides, or in clinics and hospitals. The technology allows trained radiologists to determine the baby's position, make obstetric measurements, and gather other information that allows for more personalized medical care. Once these things are known, the radiologist can recommend transferring the woman to a clinic in the area that has the proper equipment and expertise to safely delivery her baby. This greatly increases the chance of survival for both the mother and the child. Harris and Marks went to a hospital in Nicaragua to donate one of these compact ultrasound devices and within an hour, expecting mothers were lining up for a chance to be examined. When Harris and Marks returned a year later, they found that annual maternal deaths in this small community had decreased from 12 to 5.

Suggestions for using this Principle

1. Ask community leaders to include women in co-design efforts.
2. Plan activities that seek to discover the unique problems faced by resource-poor women and children in the community.
3. Pre-evaluate how the implemented solutions will positively and negatively affect the women and children in the community.

2.3.6 Principle 6: Project management techniques that are adapted to the specific developing world context enable a more effective and efficient design process.

Articulation

The design team's choice of project management strategy – and how it should be adapted to the specific developing world context – has a noticeable influence on the effectiveness and efficiency of the design process.

Support

George et al. [139] stress that investing time in project management is an important part of working with other groups, especially because of the ambiguity inherent in international development projects. As an essential part of project management, the role of each person needs to be clear and they need to be held accountable to it. George et al. also suggest that risk management strategies could be used to increase the likelihood of success. Understanding communication and cultural differences will also lead to a more successful project. Some communities, for example, are accustomed to oral communication only.

Reflecting on their multi-year project experience, George and Shams [65] promote the importance of effective project management. They provide useful tips including: (i) Begin the project with meaningful relationships; this comes through cultural education, humility, respect, and a pre-project visit. (ii) Choose a project with care; this is best done with community and NGO involvement. (iii) Have an on-site development partner; US engineers are outsiders and it takes time to build trust; on-site development partners facilitate this. (iv) Include local manufacture and materials when executing the project; these are important for achieving lasting impact. (v) Select team members carefully; members should be well prepared for the experience and should expect to learn more than just design; select team members who can contribute or learn to contribute to social change. (vi) Plan for long-term involvement and encourage previous development team members to help mentor new members through the process. (vii) Define success criteria, which should always include community approval as a primary objective. Nieuwma and Riley [100] also suggest that many NGOs and universities place a strong emphasis on education and team member exposure to new cultures. These goals do not always align with the goals of the community, which if ignored can lead to an increase in social injustice.

Additionally, George et al. [139] suggest that determining intellectual property rights at the beginning of the development project can be helpful. Blizzard and Klotz [140] suggest a framework for sustainable whole system design that could be applied to products designed for the developing world.

Many products designed for the developing world are designed by student teams in a university setting. This situation presents some unique challenges and several researchers have published their experiences working with students on this type of design project [141]–[145]. Other products are designed with the help and support of NGO workers and development workers in non-engineering fields. Other experiences and ways to measure the sustainability of projects are also found in the literature [32], [146], [147].

Example

George et al. [139] learned the importance of this principle working to help women in Mali produce shea butter and introduce it into international markets. Faculty and students at a US university started working with faculty and students at two universities in Mali and a Malian NGO. After several years of partnership, two other US universities were added to the project. This partnership of researchers, students, NGO workers, government officials, and resource-poor individuals created increased complexities in project management. George et al. learned through their experience that unclear project objectives and unclear role definitions for team members had a negative affect on effectiveness and efficiency of their projects and on how much people enjoyed being a part of the team. Having project goals and responsibilities in written form ensures that they are clearly articulated and that each team member can understand and reference them. George et al. report that increased care in communicating across institutions and cultures would have prevented repeated work and helped the sub-teams interact more effectively. Clear, written goals would have clarified expectations and prevented disappointment by helping all team members understand the university's semester schedule and the feasible possibilities for the various phases of the projects. They would also have helped all team members understand the iterative nature of mechanical design, the importance of prototyping, and the desire that local people may have to see a product working for someone else before they invest in it. George et al. suggest using project and risk management tools to overcome these challenges, but warn that these tools should not be imposed

on the community. These tools don't always work well in other cultures and US engineers need to respect that cultural difference.

Suggestions for using this Principle

1. Consciously choose, adapt, and implement a project management strategy.
2. Articulate everyone's responsibilities and hold all accountable.
3. Understand, value, and adjust to different communication styles.
4. Clearly establish success criteria, and use their measurement as a project management tool.
5. Use risk and project management tools without imposing them on resource-poor communities.

2.3.7 Principle 7: Products for the developing world have greater impact when contextualized, developed, and implemented by interdisciplinary teams.

Articulation

Impactful solutions to poverty are most often identified and implemented by interdisciplinary teams. The multifaceted nature of poverty requires knowledge, skill, and sensitivity in social, political, technical, ecological, and economic factors. Teams with such knowledge, skill, and sensitivity produce products with greater impact than those that do not.

Support

Poverty problems have been characterized in the literature as as social problems [148], [149], political problems [85], [150], [151], technical problems [70], [152], [153], ecological problems [154], [155], and economic problems [156]–[159]. Poverty problems clearly influence and are influenced by a diversity of factors. Consideration of these influences is most effectively carried out by interdisciplinary teams, where experts from multiple disciplines share ownership of ideas and cooperatively take responsibility for them [160]. Fortunately, interdisciplinary teams are not impractical since there is significant interest in poverty alleviation from many individuals in nearly all disciplines.

Although not often described as an interdisciplinary problem in the engineering literature [153], [161], [162], many researchers have reported the importance of interdisciplinary teams in achieving a lasting impact [38], [65], [77], [100], [106], [107]. George and Shams [65] report on the importance of interdisciplinary teams and say that “to make sustainable change one must understand how to contribute to social change”. They further express the frustration that “engineers don’t have this training!” Fisher also supports this idea when he describes five steps to implementing a product in the developing world [38]. The five steps are: (i) Identify profitable new business opportunities. (ii) Design equipment. (iii) Establish a supply chain. (iv) Develop a market. (v) End market subsidies. Traditionally, engineers are only trained in the second step. To have a lasting impact, poverty alleviating engineering efforts must be pursued in collaboration with individuals from other disciplines [121], or at a minimum with other disciplinary needs under consideration.

Nieusma points out that because engineers are well trained in dealing with technology, they often neglect other factors that affect the success of their products. These other factors include the culture and lifestyle of the user, social power relationships in the community, and the supply chain and distribution network of products [100]. Rarely is the engineering solution alone sufficient for lasting impact and even if the product works well technically, it has to be purchased and actually used by the customer before it can alleviate poverty.

The literature describes at least two ways for interdisciplinary knowledge, skills, and sensitivity to influence a project. The first way is through development of a team of experts from various fields [65]. The second, and least effective, is through training engineers in non-engineering activities that would otherwise be carried out by experts in non-engineering fields. The latter often leads to lower quality work because of a lack of experience and intuition that comes with years of professional practice. It is, however, better for an engineer to consider how his or her engineering solution impacts or is impacted by social, political, ecological, and economic factors than it is for him or her to not consider them at all. Cruickshank and Fenner support this claim [106].

Novy-Hildesley [107] points out that foundations are a great resource for engineers because they are a hub through which all of these disciplines can converge. Foundations offer funds, but they can also support engineers by helping them establish business plans, marketing approaches, financial and other strategies, provide legal advice, and can offer useful connections in other fields.

The work by several other researchers also supports this principle [79], [163]–[165].

Example

Postel et al. [77] share their experience with this principle. They report that 95% of the world's farmers live in developing countries and that the key to more successful farming is water management. The interdisciplinary team they established enabled them to successfully develop and distribute International Development Enterprises' (IDE) treadle irrigation pumps in rural India. One non-engineering element of the project that contributed significantly to its success was the use of Bollywood style movies rather than traditional printed ads to market the pump to rural farmers. These movies allowed information to be shared more quickly and be understood more easily. That was enough to convince people to take a risk and purchase the pumps and because the engineering was technically sound, many people were able to use the pumps to increase their farm's productivity. Engineers do not generally have training in marketing products and US engineers do not generally have training in marketing products to people in other cultures. Because Postel et al. decided to work with professionals in other fields they were able to have a greater impact. Having implemented a successful marketing approach, Postel et al. describe that the next challenges to overcome are finding a market for the increase of crops grown and increasing opportunities for micro-credit [77]. Notice that these next challenges, which enable lasting impact, require a skill set not typically possessed by engineers. Because of this, interdisciplinary teams can provide products to customers that have a greater longer lasting impact.

Suggestions for using this Principle

1. Recognize that the poverty problem being solved is influenced by multiple disciplines and factors including social, technical, political, ecological, and economic.
2. Capitalize on the wide-spread interest in poverty alleviation efforts to build an interdisciplinary team.
3. Cultivate interdisciplinary attitudes on teams by seeking collective ownership of ideas and responsibility for them.
4. Use foundations as a hub to connect with experts in other disciplines.
5. In the absence of an interdisciplinary team, team members should seek knowledge, skill, and sensitivity in social, technical, political, ecological, and economic aspects of the project.

2.3.8 Principle 8: Cooperation with governments and local influencers contextualizes and enables poverty alleviation plans.

Articulation

Poverty alleviation plans, both large and small, often require cooperation with governments and/or local influencers to be successful. This can be challenging and frustrating to design teams as socio-political objectives can often differ from the technical objectives of the design team.

Support

Decades of research has shown that rural electrification can help alleviate poverty, improve health, reduce drudgery, and increase literacy [166]. Infrastructural/systemic improvement, large or small, requires cooperation and/or funding from government and/or local influencers. Fulker-son et al. [166] present an ambitious poverty alleviation plan that requires significant government involvement to be successful. In their study of rural electrification, Fulker-son et al. introduce a 20 year, \$100 billion plan to bring sustainable energy to 1 billion resource-poor individuals who do not currently have access to electricity. The plan allows each person 0.025 kW; the US usage per capita is 1.8 kW, and the world average is 0.3 kW. If this plan were implemented, it would open an entirely new market for low power consumption appliances and other products that engineers could design to help alleviate poverty. These products would be directly influenced by decisions made by governments and local influencers.

In their study of toilet systems in India, Burra et al. [89] provide a list of obstacles to sanitation development in slums. Interestingly, they found that some governments and land owners are hesitant to improve sanitation because this attracts more people to those slums, thus compound- ing the issue and making sanitation harder to maintain. Burra et al. imply that governmental bureaucracy is often a major obstacle to implementation; politics and over-regulated funding lead to inefficiencies and this can prevent products from getting to the people who need them most. It's important to observe that governmental objectives often focus on the population as a whole as opposed to individual needs. This may influence how products are introduced into the market.

After indicating that smaller-scale technologies that help many people in small ways are needed, Akubue [34] points out that one of the main obstacles to the spread of smaller-scale tech- nology is “the existing power relations that favor advanced capital-intensive technology.” He says

that the political structure needs to change and adapt in order for small-scale technology to make a real impact. The political structure will affect the types of products that can be successfully implemented in a particular developing world setting and will affect the strategies used to implement the product.

As a different view, Margolin [17] says that real development does not come from individual products for individual families, but from higher production capacity that allow these developing countries to have a strong economy and compete in a global market. He uses Japan and South Korea as examples. This indicates that engineers can have the greatest impact by ensuring that the products they design are locally manufactured to stimulate the economy in the country they are designing for. Fisher [38] teaches that high-quality, low-cost production is needed to reduce product costs enough to be feasible for resource-poor individuals.

Harris and Marks [119] share their experience that bringing technology into a developing country can take a long time and can be expensive, with unexpected tariffs and bribes and that smaller devices are easier to get through customs. Harris and Marks teach that these obstacles should be planned for.

Considering government support from a different perspective, Uko [167] examines the value of government funding to send students from their own country to more developed countries to earn an engineering or science degree. The motivation for this is understandable as the US, Japan, and other countries have shown that engineering research is directly linked to economic prosperity. The ineffectiveness, as pointed out by Uko [167], is that most of the research these students do for advanced degrees has little to no application in their home countries. Further, the home governments often have no influence over the research performed by the students they fund. Uko also states that “effective engineering research cannot be conducted in isolation from the sociopolitical conditions of the country.” Singley [168] also provides suggestions for training engineers in the developing world.

Example

An interesting example of both positive and negative government and policy maker influence is reported by Pamuk and Cavallieri [169]. They explain that in Rio de Janeiro, Brazil many people had moved from rural areas to favelas, or Brazilian slums. In the 1960's and 70's, the government had many eradication and resettlement programs. They tried to eliminate all favelas

within 10 years by moving resource-poor individuals out of the city's center to the outskirts, which unfortunately left them with little access to transportation, employment, sanitation, and many other necessities. This program ended when the government was overthrown. The resulting political instability led to a decade of little formal policy for the favelas – a period known as “the lost decade” when there was minimal social development.

As the government stabilized, the favelas began to be upgraded under the *Favela-Bairro* Program. This program was intended to (i) provide adequate sanitation that would be maintained by the municipal government, (ii) spatially reorganize the favelas to better integrate them into existing city streets and community space, (iii) provide access to social services for people living in the favelas, and (iv) legalize land tenure. Programs such as mail service, trash collection, public lighting, and training programs for youth to learn marketable skills while improving their own communities were implemented. This helped give the program a more holistic approach and these upgrades were planned and implemented with frequent input from the people living in these areas. Here, the government intervened in a way that no other organization had the resources to do to improve the lives of millions of urban resource-poor individuals.

Suggestions for using this Principle

1. Before entering a community, find out who the local influencers are and how the design team should interact with them.
2. Find out how bribes are handled in the context of the product and decide how the design team will deal with them.
3. Find out how government and local influencers could impact the implementation of your product and form an alternative plan in case things don't go as expected.

2.3.9 Principle 9: There are existing distribution strategies that can be used to successfully introduce products into developing world markets.

Articulation

Various distribution strategies have been used over the past few decades to successfully introduce products into developing world markets. Strategies known to be successful should be used whenever possible and appropriate.

Support

To distribute a product successfully, engineers must first understand the market they are trying to reach. The literature describes three markets that product development teams typically focus on. They are:

1. Products/systems designed for communities [17], [35]–[37], [170].
2. Products designed for individuals [38], [39].
3. Products designed specifically to increase income [22], [38]–[40].

There is some debate in the literature about the impact of product development activities for each of these markets. Akubue [34] supports the well-known approach of *appropriate technology* [17], [35]–[37], [170], which is a “development approach that is aimed at tackling community problems” as opposed to individual problems. It focuses on using the resources available (labor), not scarce resources (capital, skilled labor). The appropriate technology approach has not been without criticism. Akubue [34] provides a discussion about how critics point to many examples of failed projects to say that this approach is inadequate. He also finds other drivers – not the approach itself – that could have caused the failures.

In opposition to one of the appropriate technology tenets, Fisher [38] indicates that poverty-alleviating products need to be individually owned and cared for rather than community based to have impact. He and others argue that with community owned projects, there is no penalty for people who do not contribute and no reward for people who do.

Fisher [38] and Polak [39] express the belief that the only way to effectively alleviate poverty is to help people make money. Likewise, Biswas et al., [22] and Lewis et al., [40] support the notion of income-generating products.

Once a market focus has been chosen, distribution strategies should be considered. The literature suggests several successful strategies, including:

1. Market the product in a way that is accessible to the user [77].
2. Make the product as affordable as possible [77], [171].
3. Offer flexible payment options to increase product adoption [171].
4. Use word-of-mouth to promote the product [38], [77], [171].
5. Use market subsidies initially for new products [38].
6. Include knowledge with every product sold [5].
7. Sell the product in both developed and developing markets. Use the developed market sales to subsidize the developing market sales [107].
8. Use philanthropies for legal, business, and marketing advice, as well as a source of useful contacts [107].

Postel et al. [77] describe that IDE's treadle pump was successful because they carefully considered their implementation strategy. IDE found significant success using movies instead of printed ads to promote their product. They also established the supply chain for the pumps and the parts for maintenance. Postel et al. considers these essential to development with lasting impact, because good ideas and designs won't have impact unless people actually buy and use them. Suggestions for encouraging product adoption are provided by Nakata and Weidner. They found that some factors that contribute to increased use of the product among resource-poor consumers are affordability, visual comprehensibility, flexible payment forms, and interpersonal promotions among others [171].

Fisher [38] also indicates that it is very difficult to have a successful for-profit business in this space because (i) resource-poor individuals are extremely risk averse, (ii) for-profit companies are forced to make a small profit from many people, and (iii) the initial cost to develop and sell a product is too high for resource-poor individuals to afford. He says that initial marketing subsidies help overcome these challenges.

Novy-Hildesley [107] describes distribution strategies involving philanthropic resources. Philanthropic resources allow poverty alleviating products to get to the people who need them the most by counteracting the market paradox in developing countries – large demand, yet no willing local or foreign suppliers. Unfortunately, most products wanted in the developing world are not marketable in the developed world, therefore subsidizing costs to those in poverty by selling to both markets is effective in only limited situations. Aside from funding, philanthropic resources can also include mentoring in financial, marketing, legal, and other areas, as well as connections to other people working in this space.

Example

Subrahmanyam and Gomez-Arias [5] documented many effective distribution strategies for products designed for people in developing countries. One interesting strategy they discuss is that of including knowledge with every product sold. They describe CEMEX, a Mexican cement company that sells all the building materials someone would need to build themselves a house. There are many innovations in their business model and one impactful innovation is that they offer design consultation so consumers can learn how to design and build a sturdy and comfortable house. This allows people to be independent and build at their own pace as their income allows, but also gives them new knowledge that allows them to improve their own lives. Subrahmanyam and Gomez-Arias review Maslow's hierarchy of needs [172] and provide evidence for the fact that many people in developing countries choose to fill their higher-level needs at the expense of their lower-level needs. This is because in many foreign cultures community or family is more important than self [173]. For example, families will sacrifice things they need so they can send the children to private schools [5]. Providing knowledge with a product fills a higher need. This can lead to more implementation with more lasting impact than selling the product alone because people are more willing to spend their money if their purchase fills more than just a basic need.

Another example of including knowledge and self-development in a product is Danone's single serving yogurt in Bangladesh [5]. Women are trained to sell this product, but they are also trained in nutrition. As they sell their yogurt, they pass this knowledge on to other members of the community. *Including knowledge with every product sold* is just one of many distribution strategies that have been documented and can be used by designers to more sustainably implement their products.

Suggestions for using this Principle

1. Research the distribution strategies that have been successful for similar products in your specific setting.
2. Examine the list of existing distribution strategies presented in this section and decide which is best for your specific project, if any.

2.4 How the Nine Principles Relate to Traditional Design Principles

In the previous sections, we have examined the nine principles and have discussed their importance in the context of design for the developing world. To further explore the nature of these principles, we now categorize them in relation to traditional design principles often associated with the *developed world*. We use the three concentric ovals illustrated in Figure 2.1 to facilitate this discussion. Each of these ovals is discussed in the following subsections as a way of relating the nine presented principles to traditional design principles.

2.4.1 The Generic Solution Finding Process

In the center of Figure 2.1, we see a generic representation of the basic solution finding process which consists of four steps; (1) requirement establishment, (2) solution generation, (3) solution evaluation and selection, and (4) solution embodiment. Generally in the design process, these basic solution finding steps will be executed often and at various times and scales. The process is often iterative where requirements, generation, and evaluation/selection steps may be executed multiple times to identify a desirable solution that merits embodiment in the product. The four step process exists for the purpose of identifying and embodying desirable solutions to the design problem at hand.

The engineering literature provides various traditional design principles aimed at guiding the engineer through the design process. While we do not claim the review of these traditional principles to be comprehensive, we sampled several major works on the topic [47], [103], [104], [174]. Through this review, we identified 35 unique design principles. Of these 35 principles, 30 apply to the generic solution finding process shown in the center of Figure 2.1. These 30 principles

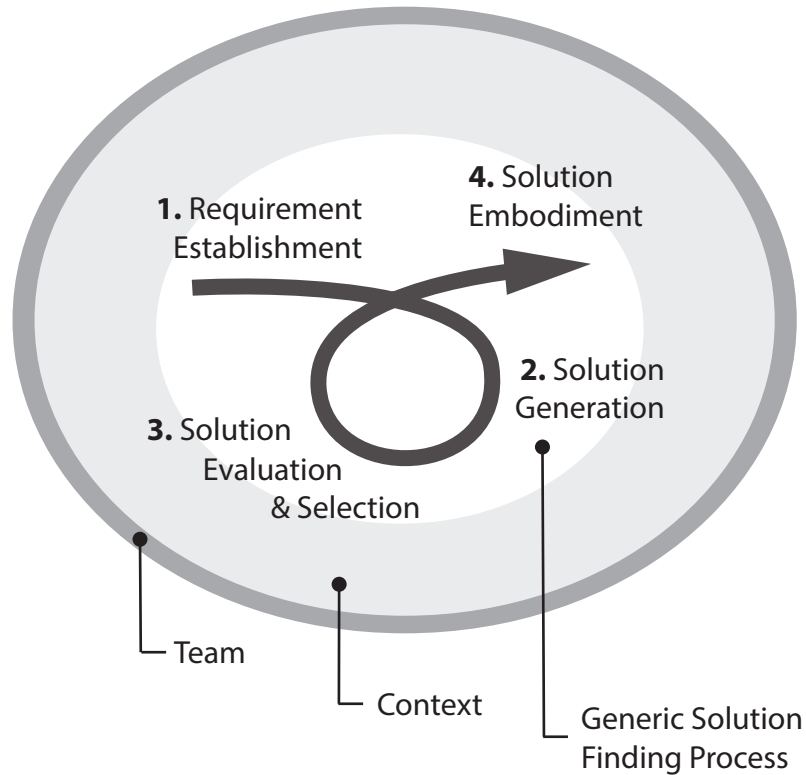


Figure 2.1: Three concentric ovals representing (i) a generic solution finding process (center), (ii) the context for the problem and solution (inner ring), and (iii) the team that contextualizes and develops the solution (outer ring). This figure facilitates the discussion in Sec. 2.4.

are listed in Table 2.2 at the end of this chapter. Of the remaining five principles, four apply to the context and are stated below. The context is shown as the inner ring in Figure 2.1. The remaining principle applies to teams that value a diversity of expertise, shown by the outer ring.

We believe it is valuable to consider all of these traditional principles useful for developing world projects – they support finding a technically sound solution to the design problem. We also believe, however, that to have impact in the developing world, solutions must be both technically sound *and* desirable to those who will use or purchase them. Interestingly, at their core, none of the nine principles presented in this chapter are about technical soundness as achieved by the solution finding process in the center of Figure 2.1. Instead, they are fundamentally about the context of the problem and the solution – the understanding of which is necessary for achieving a desirable solution in a developing world setting.

2.4.2 The Problem and Solution Context

The inner ring of Figure 2.1 represents the problem and solution context, hereafter referred to simply as context. Only when the context is established and understood can the solution finding process (center of Figure 2.1) produce a valuable outcome. The context is the set of circumstances that form the setting for the solution. Without an understanding of the setting, it is impossible to know if a given product can or should be implemented.

It is important to recognize that requirements and context are not the same thing. To solidify this idea, consider this context (or circumstance that forms the setting): Many people in Burundi earn less than \$271 annually. This context informs – but is not itself – a requirement. The informed requirement for a disposable medical device, for example, could be that it costs less than \$0.05 for an impoverished Burundian to purchase. This requirement is informed by the low-income context.

In one respect, it is surprising to find very few principles in the literature that guide the engineer to understand the context for *developed world* products. On the other hand, this is not surprising since the engineer has typically lived his or her entire life in the developed world context and can relate to it naturally and intuitively. Creating products for the developing world, however, requires the engineer to understand and design for a context that is not at all natural to him or her.

Most engineering projects for the developing world do not fail because of the mechanics of the generic solution finding process. They fail because of a weak understanding of the context. This lack of understanding unfortunately leaves little opportunity for the solution finding process to produce a valuable outcome.

Several of the nine principles presented in this chapter help the engineer understand the context for developing-world products. We now relate them to four of the traditional principles not yet discussed nor listed in Table 2.2. These four traditional principles are listed below in italic text, followed by the principles from this chapter that apply to them.

Designers are responsible for the impact of their product on others [94], [103]. This principle refers to the people for whom the product is designed. It includes those for whom the product is directly designed and those around them who may be indirectly affected by it. Four of the nine principles presented in this chapter (in whole or in part) are fundamentally centered on how the product impacts people in the developing world context. They are:

- Principle 1 in part: Co-design with people from the specific developing world context promotes user ownership, and empowers resource-poor individuals.
- Principle 3 in part: Importing technology without adapting it to the specific developing world context is ineffective.
- Principle 4: Both individuals in urban and rural contexts can benefit from poverty alleviation efforts.
- Principle 5: Women and children are more affected by poverty alleviation efforts than men.

Design decisions affect all people in the downstream development [103], [174]. This principle refers to everyone directly involved in the product development process. Three of the nine principles presented in this chapter are fundamentally centered on how the decisions made during one stage of the product development process affects other product development efforts downstream. They are:

- Principle 3 in part: Importing technology without adapting it to the specific developing world context is unsustainable.
- Principle 6: Project management techniques that are adapted to the specific developing world context enable a more effective and efficient design process.
- Principle 9: There are existing distribution strategies that can be used to successfully introduce products into developing world markets.

Acquiring knowledge is costly and compromise regarding how much can be economically acquired may be necessary [103]. This principle refers to knowledge and understanding about the context and the solution. Two of the nine principles presented in this chapter are fundamentally about how the acquisition of knowledge is more effective when centered on the actual setting and the people living within it. They are:

- Principle 1 in part: Co-design with people from the specific developing world context encourages designer empathy.

- Principle 2: Testing the product in the actual setting is an essential part of design for the developing world, not merely a final step.

Designers are responsible for the natural resources used in their products [103]. This principle refers to how the product will deplete, maintain, or reuse natural resources from the local developing world setting or from the global setting. Interestingly, we did not find a pattern of emphasis for this principle in the engineering-based developing world literature that we reviewed. Therefore, none of the nine principles presented in this chapter are fundamentally about our responsibility for our use of natural resources. This is not to say it is unimportant, or that it is never mentioned in the literature. It is to say, however, that it has not yet been a central repeated theme that engineering researchers have emphasized as essential to developing world efforts.

In this section we have categorized seven of the nine presented principles as helping the engineer better understand the context for the problem and solution. Referring back to Figure 2.1, we reiterate that only when the context (inner ring) is established and understood, can the solution finding process (center) produce a valuable outcome. To that end, it is essential that the context continually influence all parts of the solution finding process.

2.4.3 The Team

The outer ring of Figure 2.1 represents the team of people who will discover the context (inner ring) and find solutions (center) to developing world design problems. The ability to discover that context well and identify highly desirable solutions efficiently is completely related to the composition of the team that attempts to do it. The two remaining principles presented in this chapter apply to the team:

- Principle 7: Products for the developing world have greater impact when contextualized, developed, and implemented by interdisciplinary teams.
- Principle 8: Cooperation with governments and local influencers contextualizes and enables poverty alleviation plans.

Table 2.1: Summary of Principles

Principle (shortened)	Supporting Citations
1. Empathy through Co-design	[65], [89], [93], [96], [100], [105]–[115]
2. Importance of In-Context Testing	[49], [65], [89], [93], [117]–[128]
3. Risk in Technology Importation	[5], [79], [84], [100], [108], [119] [33], [34], [122], [129]–[133]
4. Rural and Urban Opportunities	[38], [77], [89], [106], [137], [138]
5. Effects on Women and Children	[77], [89], [93], [119]
6. Project Management Strategy	[32], [65], [100], [139]–[147]
7. Interdisciplinary Teams	[38], [65], [77], [100], [106], [107] [121], [153], [161]–[165]
8. Cooperation with Government	[17], [34], [38], [89], [119] [166]–[169]
9. Existing Distribution Strategies	[5], [17], [22], [38], [77], [107] [34]–[37], [39], [170], [171]

The literature shows that teams consisting of multiple disciplines and local influencers are more capable of properly contextualizing the problem and can therefore generate more effective and appropriate solutions [103], [104], [174].

2.5 Concluding Remarks

As gleaned from the published literature, this chapter has examined the work, experiences, and insight of various researchers and practitioners working in the area of design for the developing world. We have observed recurring themes within the examined work and summarized them in the form of nine principles for effective design for the developing world. Table 2.1 shows the nine principles in shortened form, with reference to the supporting citations. We feel that these principles – some of which are intuitive and some of which are not – represents the state-of-the-art in published design principles for engineers working to alleviate poverty.

We have also provided a list of suggestions for how to use each principle in day-to-day design and engineering practice. We believe that individually or as a compilation these lists provide a useful set of suggestions for any novice or expert searching for greater product impact and sustainability in the developing world. We have also shown how these nine principles relate to traditional design principles.

The work done to alleviate poverty through engineering could also be divided by product areas rather than by these principles. Some of the product areas with the most work related to them found in the literature are cookstoves and charcoal production [175]–[185], food processing [186]–[189], medical products and telemedicine [110], [163], [190]–[202], manufacturing systems [203]–[206], lighting [97], [207]–[211], electrification [120], [212]–[237], and mobile phones and Information and Communication Technology (ICT) [136], [238]–[244]. There are also several publications about poverty in general that may help us understand what role we as engineers can play in alleviating poverty [245]–[257].

Over a period of several years we have been involved in the design of 28 different mechanical products for resource-poor individuals in various places including Brazil, Peru, Tanzania, and India. Our experiences are consistent with the nine principles presented in this chapter. At times, we have produced products with large impact because we followed these principles, and at other times we have failed to produce impactful products because we did *not* use these principles to guide our efforts. We agree with each of the nine principles and believe that they will help any engineer who wishes to design products for or with resource-poor individuals in the developing world.

Although the survey of the literature in the area of design for the developing world was comprehensive, the nine resulting principles are not. Undoubtedly there are other principles that can and should guide engineers as they design products for the developing world – but these are not yet found in the engineering literature. We believe that new principles are likely to be identified for each of the ovals illustrated in Figure 2.1. For example, as more is learned about the efficiency and effectiveness of interdisciplinary teams solving developing world problems, new principles will come to the fore. The same is true for the problem and solution context, wherein we are likely to observe regionally-specific principles emerge. Even new principles that guide the solution finding process may be identified and be specific to the developing world setting. As an illustration, it's possible that the well-known design for assembly principles related to reducing part count may have opposing principles that apply only in the developing world. *Increasing* the part count is arguably desirable in locations where the objective is to create jobs and grow local economy. In this sense, we believe that some traditional principles will be challenged and new, more appropriate principles specific to the developing world will be found.

We also believe there exists a difference between what appears in the archival literature and what non-publishing practitioners do. For example, practitioners appear to invest more time and money in pre-engineering need finding through travel compared to academic researchers. This leads to holes in the literature and unanswered questions such as: What principles guide need finding for engineering in the developing world? What role does travel play for the engineer? And what principles guide the decisions to send an engineer on a pre-engineering need finding trip versus a mid-development validation trip versus an implementation trip at the end of a project? Principles that can be used to guide the decision making regarding these questions would be very valuable to engineers.

In gathering the nine principles, we have been careful to only present principles with multiple sources of support. We chose this approach because it produces a general pattern found to be true in multiple cases. As a drawback, this approach misses potentially valuable principles that are not broadly discussed. As the literature in this area grows, more and more evidence will be given for new principles. We believe, for example, that more principles will be identified regarding the designer's responsibility to the natural resources used in the product.

While the literature shows a pattern for the nine principles presented in this chapter, there is still much that needs to be learned before we as engineers will become routinely effective at designing for the developing world. To that end, we invite and encourage academics and practitioners to critically evaluate their own developing world engineering experiences – and share that evaluation in the archival literature – so that they can influence others in their pursuit to design more impactful products for resource-poor individuals.

2.6 Additional Information for Analysis of Traditional Design Principles

In Table 2.2, we list the traditional design principles. This list is not comprehensive but does include all the principles found in a few key traditional engineering design texts [47], [103], [104], [174], [258]. These principles are divided into the four steps of the generic design process.

Table 2.2: Traditional Design Principles for the Four Steps of the Generic Solution Finding Process

Principle	Citations
Traditional Principles for Requirement Establishment	
Understanding the basic need before creating solutions, for it leads to more effective and efficient solution generation.	[94], [103], [174]
Good designers are aware of and influenced by existing designs.	[103], [174]
Risk is lowered when all functions are unambiguously specified, in form, parameters, manufacturing and assembly.	[104]
Proficient designers have a broad understanding and appreciation for multiple disciplines.	[47]
Traditional Principles for Solution Generation	
The best concept is typically found only after a large set of concepts are considered.	[103], [174]
Many generated concepts will be poor and not incorporated in the final design.	[103], [174]
It is difficult and inefficient to transition a poor concept into a good product.	[103]
A strong concept is the foundation upon which a great product is built.	[103]
It is more efficient to use a suitable existing component than to design a new one.	[94], [103]
When existing solutions are not suitable, they may become so through simple redesign.	[103]
Opportunities for innovation exist at the boundary of feasibility.	[103]
Traditional Principles for Solution Evaluation and Selection	
It takes a significant amount of thought and time to evaluate candidate solutions.	[103], [174]
There are many satisfactory solutions to every design problem.	[103]
It is costly to keep many concepts in consideration.	[103]
Tradeoffs exist and will need to be managed.	[103]
Some important criteria can't be measured.	[103]
Joint ownership in decisions is valuable to downstream development.	[103], [174]
Traditional Principles for Solution Embodiment	
Complexity occurs primarily at interfaces.	[103], [104]
The number of interfaces increases with the number of components.	[104]
Every fastener increases cost and decreases strength.	[103]
How forces are transmitted through any part is important.	[47], [104]
Loads are effectively transmitted through triangles.	[47], [104]
Many mechanical designs experience failed amounts of elastic deflection before failed amounts of stress.	[47], [104]
Unwanted vibration can be reduced by reducing vibration at the source, changing the transmission of vibrations from the source to other parts, or by reducing the transmission.	[47]
Whether a part in an assembly moves freely or binds is completely determined by the interactions of component weight, frictional force between components, and applied force between components.	[47]
All components are positioned and constrained.	[47]
It is not useful to over-constrain components.	[103]
Shared modules across product lines are the basis (platform) for a product family.	[47]
The most modular system is one where each function is embodied by exactly one module.	[259]
Function determines form and form enables function.	[103], [104]

CHAPTER 3. DESIGN FOR THE DEVELOPING WORLD: COMMON PITFALLS AND HOW TO AVOID THEM

3.1 Chapter Overview

Engineers face many challenges when designing for the developing world that are not typically encountered in other design circumstances, such as a lack of understanding of language, culture, and context. These challenges often prevent engineers from having a sustained impact as they design for resource-poor individuals. In this chapter, reports from 41 engineering projects in the developing world were analyzed and common pitfalls were identified. The data came from Failure Reports from Engineers Without Borders Canada and from the authors' own field reports. After the pitfalls are described, the authors present a visual tool called the Design for the Developing World Canvas to help design teams that are developing manufactured products to avoid these common pitfalls. This canvas can be used throughout the product development process as part of regular design reviews to help the team evaluate their progress in advancing the design while avoiding the pitfalls that engineers commonly face.

3.2 Introduction

The engineering profession plays a significant role in global development. One particular area of global development – poverty alleviation in developing countries – has interested many engineers from the developed world who are eager to use their skills to design affordably-priced products that help resource-poor individuals [42]. Despite this desire, these engineers face several unique challenges when designing products for the developing world that can limit their impact. Such challenges include barriers in language, culture, context, and large geographical distances [260].

The purpose of this chapter is to identify and articulate common pitfalls of design for the developing world, and to present a simple tool to help design teams avoid them. Some common

pitfalls were identified by examining Failure Reports [49], [124]–[127], [261], [262] from Engineers Without Borders (EWB) Canada and field reports from projects carried out by the authors. The pitfalls were then used to construct a visual tool – termed a *canvas* – to help design teams consider the facets of product development needed to avoid the pitfalls.

The concept of a canvas comes from the *Business Model Canvas*, which was first introduced by Osterwalder and Pigneur [50] and quickly became popular as a visual way to consider and communicate each part of the business model. The present chapter uses data from numerous engineering case studies to construct an engineering-related canvas – akin to the Business Model Canvas – that is created to help design teams avoid the pitfalls that have caused many previous engineering projects in the developing world to have little or no impact.

Within the engineering literature, Mehta and Mehta [263] present the E-Spot Canvas as a way to help stakeholders in developing world projects – namely designers, implementers, and end-users – to find a desirable balance regarding stakeholder equity, meaning which stakeholder will provide what quantity of time, money, and sweat-equity to the project. This tool is useful for helping stakeholders determine expectations and responsibilities before the project begins and does not focus on the overall product development process. The canvas presented in the present chapter serves a different purpose – to help design teams periodically evaluate their progress in advancing the design while avoiding the pitfalls. The canvas introduced in this chapter is called the Design for the Developing World Canvas and is specifically for teams designing manufactured products, but may also be useful for teams working on programs or services.

3.3 Research Method

In 2008, EWB Canada published their first Failure Report [49]. The purpose of this report was to share past failures with the goal that these failures would not be repeated by other engineers. After a positive response from the engineering community, it was decided that a similar report would be published each year. These reports document the experiences of practitioners working in the field on developing world projects. Most of these practitioners were hired as fellows and spent 12 to 20 months working in the field. The authors chose to study these reports from EWB Canada because, unlike projects often published in academic journals, these reports focus specifically on

the challenges encountered and the mistakes made rather than highlighting the positive outcomes of the project.

Between 2008 and 2014, a total of 72 articles have been published through the annual Failure Report. Of these 72 articles, 27 described projects implemented in a developing world setting. The remaining articles consisted of failures in management within EWB Canada, failures in the organization of various student chapters of EWB Canada, and personal failures that may have occurred in a developing country but that did not give any specific information about the project being implemented. The authors of the present chapter were careful to focus only on the challenges engineers face in working in a developing world context and not on the challenges engineers face when working within a Non-Governmental Organization (NGO) or when working on related projects in their home country (for example, advocacy and fundraising activities). This chapter also examined 14 field reports for developing world projects completed between 2011 and 2014 by the authors; these reports were written during and immediately after the field work. A total of 41 cases were studied.

The authors examined a report for each project and extracted statements – either phrases or sentences – that explained the causes of failure for each project. This level of data granularity was chosen because it provided sufficient detail to understand the context and cause of failure. As often as possible, these statements were taken verbatim. For all projects combined, this generated a list of 225 statements. Redundant statements within a given project were then combined. For example, if a particular project had multiple statements referring to the same failure mode, these were combined into just one statement. Doing this for each of the projects individually reduced the set of statements from 225 to 142.

These 142 qualitative statements were then organized into themes using the KJ Method, which was developed to help reveal themes in ethnographic data from Nepal and often results in an affinity diagram [48]. This was done by a group of four researchers with experience in design for the developing world. Ultimately, 7 distinct themes emerged and each of these themes is articulated as a pitfall in the following section. By three sets of statistical correlation tests, the 7 pitfalls were deemed sufficiently independent to stand as unique pitfalls (see Section 3.4). The 7 pitfalls do not encompass *all* of the pitfalls an engineer may face in designing for the developing world; these are only the pitfalls found in this rare and valuable data set.

Any study that makes observations from human generated data, such as the data reviewed in this chapter, must recognize the potential for researcher bias. While extracting the 142 statements from the 41 cases, the researchers made a conscious effort to use a *non-judgmental orientation* [57]. A non-judgmental orientation requires the researchers to suspend personal valuation of any given cultural practices – especially to avoid the assumption that one practice is superior to another. In this case, the cultural practice is the design practice or philosophy of those who created the 41 case studies. While the authors have taken these measures to prevent contaminating the data, it is recognized that bias cannot be fully eliminated.

Upon identifying the 7 pitfalls, a product development focused canvas called the Design for the Developing World Canvas was specifically created to help design teams avoid the pitfalls. To identify the key product development facets to include in the canvas, the authors (i) benchmarked the few existing canvases [50], [264], [265] to identify potential facets, (ii) evaluated those facets against the pitfalls, and (iii) added additional facets to support the unaddressed pitfalls. The choice of which facets to include was also influenced by traditional product development methodology and the authors own product development experience in the developing world. The layout of the canvas (described in Section 3.5) was chosen to subtly emphasize the coupling between its parts. All facets were chosen to ultimately help the design team avoid the 7 common pitfalls.

3.4 Pitfalls

In this section, the 7 common pitfalls are described and several examples from the cases are given for each. In the table below, each of the pitfalls is articulated and a percentage is included; this percentage represents the number of statements extracted from the data related to that pitfall divided by the total number of statements.

It should be noted that in most cases reviewed, more than one pitfall was identified. Also notice that the first 3 pitfalls represent 78.9% of the statements. This was similar for both data sets with 77.5% of statements from EWB Canada and 80.3% of statements from the authors field reports supporting the first 3 pitfalls. While the percentage of the last 4 pitfalls is significantly smaller in both data sets, they were reported in several cases. As such, this chapter provides a more detailed discussion of the first 3 pitfalls and a shorter discussion of the last 4. The 7 pitfalls presented do not represent an exhaustive list, since they are derived from a particular data set based

Table 3.1: The 7 common pitfalls with the percentage of statements from the reports analyzed that reflect each pitfall.

	Common Pitfalls	Percent
1	Lacking the contextual knowledge needed for significant impact	28.9
2	Neglecting to make a plan for or developing partners for long-term sustainability	26.1
3	Assuming the needs of the customers being served	23.9
4	Not making a plan for or developing partners for manufacturing	7.7
5	Lacking skills or expertise for a specific project	5.6
6	Miscommunicating or failing to develop trust with local stakeholders	4.9
7	Forgetting that communities change over time between field visits	2.8

on the experiences of practitioners working in a non-profit context. Other studies by the authors examine other data sets [42]. Also, while the data used to identify the 7 pitfalls comes only from developing world projects, these pitfalls may also apply to design in the developed world.

To show that the 7 converged-upon pitfalls are practically independent and that no further combining of pitfalls is needed, the authors carried out three sets of data correlation tests: the Pearson linear correlation test [266], the Spearman monotonic correlation test [267], and the Kendall rank correlation test [268]. To carry out the tests, a matrix was created where the 41 cases were represented in the rows of the matrix, and the 7 pitfalls in the columns. The number of pitfall occurrences for each case were recorded in the body of the matrix. For example, case 1 had three occurrences of pitfall 1, one occurrence of pitfall 5, and no occurrences of the other pitfalls. Each column of the matrix was compared to every other column of the matrix to reveal the correlation between pitfalls and cases. From a practical point-of-view, this means that the authors examined whether any two pitfalls tended to occur at the same time, indicating that they should be combined.

All of the tests revealed weak correlations in the data set, except in two cases where a moderate linear correlation is found between pitfalls 2 (sustainability) and 3 (customer needs), and a moderate monotonic correlation between pitfalls 3 (customer needs), and 7 (forgetting that communities change over time).

Table 3.2: All non-weak correlations observed between pitfalls.

Correlation Test	Pitfalls Involved	Correlation Coefficient (r)	p-value (p)
Pearson Linear Test	2, 3	0.3886	0.0100
Spearman Monotonic Test	2, 3	0.3571	0.0188
	3, 7	0.3197	0.0366
Kendall Rank Test	2, 3	0.3131	0.0212

The pertinent results are shown in Table 3.2. To find meaning in the table, recognize that a correlation coefficient (r) of 0 means no correlation and that a value of 1 means strong positive correlation. The authors adopted the traditional view for ethnographic data that $0 \leq r < 0.3$ represents a weak correlation, that $0.3 \leq r < 0.6$ represents a moderate correlation, and that $0.6 \leq r \leq 1$ represents a strong correlation. Regarding the p-value statistic (p), the authors assume that $p \leq 0.05$ provides evidence that the observed correlation is not random.

The important thing to observe from this data is that in all cases the pitfalls – even those with moderate correlations – are sufficiently independent to be characterized as unique pitfalls.

3.4.1 Pitfall 1: Lacking the contextual knowledge needed for significant impact

In 28.9% of the statements, a lack of contextual knowledge led to failure. Contextual knowledge includes knowledge of the history and culture of the community. For the purpose of this chapter, this pitfall is not related to customer needs, which is discussed in Pitfall 3. It is related, however, to understanding the local norms and conventions that determine how engineers should operate in a particular context. This was the most pervasive problem in the cases analyzed. Cultural nuances are most effectively learned by spending time in the context where the project will be implemented, but this is expensive and time-consuming. Because most projects in the developing world are carried out with limited resources, it is understandable that this challenge is encountered so often but it is important for engineers to realize that contextual knowledge, or lack thereof, has a significant impact on how well a project will be accepted and adopted in a community.

Examples of Pitfall 1

There are many examples from the cases where a lack of contextual knowledge led to failure. In Malawi, engineers worked with a rural entrepreneur to improve his cassava processing facility. The engineers first focused on the machinery, but then began to teach about business and supply chain management. This rural entrepreneur learned some useful skills and was able to temporarily increase his income, but the training he received did not allow him to sustainably grow his business so his improved cassava processing facility soon sat idle. Reflecting on this experience, one engineer said that she had “learned that the factory, while small and seemingly straightforward, is part of a much larger complex system of community dynamics, financial norms, interpersonal relationships, and Malawian society. Without appreciating it as such, we came up with a pretty blunt and inadequate solution to a complex problem” [269]. Understanding the history and culture of a community and how groups in that context interact with each other allows engineers to develop solutions that sustainably integrate into the context of a community.

In another case, a group of engineers attempted to collect feedback on a product they thought would be helpful to rural farmers. Customers were responding well during field tests, indicating that this area might be a viable market for the product. Later, the engineers received feedback from customers who had purchased the product. Some customers said that they decided to purchase the product, not because they thought it would be useful to them, but because it was a “cool, American invention”. The engineers did not expect to have this cultural difference affect their field tests.

Events in one community such as elections, re-elections, and several major holidays meant that local workers could not be trained when originally planned. This delayed the start of the project for almost 3 months [270]. These delays are more commonly accepted in other cultures, but are not often accounted for in Western engineering schedules.

In another case, engineers implemented a pilot program in one region. After it was shown to be successful there, the engineers expected to be able to partner with the local government to implement it in the surrounding regions. They later found that this was not possible because of the funding structure of local governments. In this context, local governments receive funding for specific projects from the national government and from donors and any money received must be spent on that specific project. Because the local government had no flexibility, they were not able

to divert funds to the new program even though it had been shown to be successful. The engineers did not understand this funding structure before implementing the program and were not able to expand the program because of it [271].

One engineer said that their project failed because “we were in a hurry, we were overconfident, we didn’t have adequate cultural or historical knowledge, and we didn’t do the homework that might have told us in advance what we were going to learn the hard way” [272].

Another important aspect of the local history is projects that have been implemented in that community in the past by other groups. In most situations, engineers will not be the first group of outsiders to come into a community with the intention of having a positive impact. Past experiences with similar groups will affect the expectations of community members and should be considered by the engineers before they begin. In one case, engineers had successfully implemented a program and were planning a small celebration for the community with the modest budget that remained. When it became clear to the community leader that the community would not be getting an elaborate party, which a previous group had provided, he was upset because his expectations were not met and he encouraged community members to discontinue their participation in the program [273]. If the engineers had known this local history earlier, they would have been able to handle the situation without offending community members or affecting the impact of the program.

3.4.2 Pitfall 2: Neglecting to make a plan for or developing partners for long-term sustainability

In 26.1% of the statements, engineers worked on projects that required a long-term plan, often far longer than the engineers could stay in the community. A lack of community partners to implement the project long-term often leads to unfinished projects or projects that have very low impact. Projects may also require that a certain level of customer service be offered with a product. When the engineers are not in the community over an extended period of time or when engineers do not have the skills or language ability to offer that customer service, the project is not likely to have a significant impact.

In the cases studied, there were several specific causes of failure related to this pitfall. Listed from most common to least, they are:

1. Lacking the channels for delivery
2. Inappropriate program strategy or structure
3. Ineffective transfer of responsibility to local stakeholders
4. Lacking the resources or partners to scale up
5. Depending heavily on the skills of a single person
6. Lacking continuity between volunteers or other workers

Examples of Pitfall 2

In many of the cases, having no way to deliver/distribute the product or service was the major cause of failure. In these cases, the product or service was working but there was no way to get it to the people who needed it. In Zambia, an engineer helped to deliver a planer to a carpenter living in a remote area. The planer was installed incorrectly, destroying a critical component and leaving the planer inoperable. The engineer did not establish a system for repairs and had no plan or partners for long-term sustainability. Because the carpenter lived in such a remote area and because replacement parts and repair expertise were not readily available, it was 4 months before the planer was fixed. The carpenter was not pleased with the service he had received and having such expensive equipment sitting idle meant it was not having the intended impact [274].

In other cases, projects had an inappropriate strategy or structure for the context in which they were implemented. In one example, an engineer was asked to help rural entrepreneurs gain access to expensive machinery that would help grow their small businesses. The engineer started a non-profit organization and later decided that a for-profit model would lead to greater accountability and success. But as a for-profit company, he reported that there was no mechanism for him receive donations from other non-profits. In order to continue purchasing the equipment that would help his customers, he was forced to spend his time focusing on the activities that would be most profitable to keep the business going instead of spending time in the field getting to know his customers and their needs. In reporting his experience, he says that he made the switch to a for-profit organization too soon and should have remained a non-profit so he would have had more

freedom to spend time learning from his customers in the field. In this case, the structure of the organization was inappropriate for the desired impact [275].

In several cases, unsuccessful attempts at transitioning leadership of a project to local partners was the cause of failure. In several cases, this transition was difficult because the local partner, a regional government, did not have the funds to support the program once the engineers left [273], [276], [277]. In another case, the local partners did not have the training to support the program [271]. In one case, an engineer implemented a program in a community and the program was successful while the engineer was present. Because of this, he expected the local government to continue it when he left, which they did not. Looking back, he says that his team failed to work within the constraints of the local government. The engineers had proven the program to be successful but maintaining it was outside of the budget the local government so when the engineer and his funding left, the program was discontinued [273].

Some cases showed that the cause of failure was related to challenges faced when scaling up a project. In one case, an engineer had developed a training program that would help rural farmers market their produce more effectively. He saw that the program was useful but it needed to be implemented by government workers who would be the ones actually training the farmers. He tried to implement the program in one area but had little success with the government workers there so he decided to try the program in a few surrounding areas, hoping that if the program went well in other areas the original area would be more inclined to participate. The program was still evolving to meet the needs of farmers in this area and in the end, the engineer said he had involved too many people before the program was ready. He tried to scale up too quickly and said that in the future, he would work with a smaller group of highly motivated government workers while making adjustments to the program and focus on spreading the program when it was more refined [270].

Several cases highlighted a project relying too heavily on the skills of a single person as the major cause of failure. This can be dangerous to the sustained growth of the program because if that one person leaves, the project is likely to end. This almost happened in the case of an agricultural school that helped farmers increase the profitability of their farms. Farmers were having success with the program and the program was growing when one of the key instructors was offered an opportunity to pursue a graduate degree and abruptly left. No one else at the school was qualified to teach those important classes and they thought the program would soon end [278]. In this case,

they were able to find another instructor at a nearby university to teach and keep the program running, but in many cases the program ends when the one spearheading it leaves. Partnering with others and training them, particularly those who are already a part of the community, to manage a program can be an effective tool in improving sustainability.

3.4.3 Pitfall 3: Assuming the needs of the customers being served

In 23.9% of the statements evaluated, the pitfall of the project was that engineers made assumptions about what resource-poor individuals in the community wanted. These assumptions are often based on a limited familiarity with the lifestyle, opportunities, and challenges of those living in poverty. Engineers will be more effective as they understand the problem from the perspective of resource-poor individuals before trying to solve it.

Examples of Pitfall 3

One example that clearly shows a lack of understanding of customer needs was reported by an engineer who raised money to fund a computer lab in Tanzania. Ten computers and a solar power system were installed. During a site visit six months later, he learned that the computer lab had failed to have a positive impact in this community. Three of the computers had been stolen, two had been infested with local ants, and two others had so many viruses that they were not functional. Only three of the computers were still operating but they were locked in an office where they would be kept safe, but were inaccessible to community members. While reflecting on this failure, the engineer says his group “failed to learn in advance what sort of computer lab they might want in their school (instead, we made assumptions from 8,000 miles away)” [279].

In another situation, engineers developing a food processor made the assumption that the processor had to be manual because it was going to resource-poor individuals. While testing it in the field, several community members suggested that the machine be electric so that the food processing would be easier. People in this community had access to plenty of electricity and were willing to use it for processing food. This is certainly not true for all developing communities, but engineers should discuss these things with resource-poor individuals before beginning the project instead of making unsupported assumptions.

A group of engineers were trying to make the process of washing clothes less labor intensive and time consuming, so they developed a hand-powered washing machine. They assumed that the look of the product wouldn't matter much to the people in the community as long as the machine was inexpensive and performed well. When the engineers tested a prototype in the community, it quickly became clear that, while washing clothing is a significant challenge for people there, they were not interested in this prototype. It was constructed of "cheap" materials causing the people in the community to feel that it would not last long and was a poor investment. In response, the engineers redesigned the machine using higher quality materials. Although this redesign almost tripled the cost of the machine, people in the community were much more willing to purchase it because it looked professional and durable.

Several engineers reported that working closely with their customers often and in the customer's context helped them stay focused on what their customers actually need [280], [281]. In a related case, the engineers were in the field developing a small kiln to fire pottery as a way to increase income. While the engineers had lived in the community for 3 months and had access to end users, the kiln was heavy and difficult to transport, which discouraged them from taking it to potential customers for feedback. This lack of feedback meant that the engineers had to make design decisions based on unsupported assumptions which led to a product that was not as successful as it could have been with more user input.

Another assumption engineers commonly make is that *any* solution to the problem is better than what people in the community already have. This is simply not true. In one case, engineers assumed that resource-poor individuals would be willing to spend one full day of each month maintaining a water filter in order to have clean water. While the filter worked well and was proven to prevent illness in this community, over time it became clear that resource-poor individuals in this context were not willing to accept this extra inconvenience in order to consistently have clean water. Their need for convenience was overlooked by engineers who assumed that any solution was better than nothing.

3.4.4 Pitfall 4: Not making a plan for or developing partners for manufacturing

For engineers designing a physical product, manufacturing in the developing world poses a significant challenge. While this only represented 7.7% of the statements, it is still a pitfall worth

recognizing. If a product is designed but there is no plan for the manufacturing of it or there are no partners with the capability to do the manufacturing, the product cannot be distributed to resource-poor individuals who could benefit from it.

Examples of Pitfall 4

In several cases, products failed because the necessary parts were not available locally or because local resources and manufacturing capabilities were different than expected. In one case, a pump was made using pipe that required a very tight tolerance to create a seal. The variation in wall thickness was much greater in the local pipe than the engineers expected and this prevented the pump from sealing properly. This difference in locally available materials had a significant impact on the team's plan for manufacturing.

In another case, the engineers wanted to use local materials to build a fruit press. Because wood is a common construction material in the particular community, the frame of the press would be made of wood by a local carpentry shop. Plans were sent in advance but when the engineers arrived in the community weeks later, the carpenter had not completed the order as planned. This problem was not a matter of miscommunication. Rather, the problem was that the partnership was not developed enough for the carpenter and the engineer to work effectively together. The carpenter was able to produce the needed parts before the engineers left, but not having the parts ready slowed the engineers' progress. While this team had found a local carpenter, they had not yet built a partnership with him that would allow the product to be manufactured at a higher volume and have a significant impact.

Another problem mentioned in the cases was the difficulty in communicating to local manufacturers the dimensions of the parts. In one case, the engineer entered a welding shop with engineering drawings made in a computer aided design (CAD) program. He gave the drawings to a welder and after a few moments, realized that the welder did not understand the orthogonal views. While this is not universally true in the developing world, in this case the welder was not accustomed to this type of drawing. Instead, he preferred to hand-sketch isometric views of the parts in his notebook while talking to the engineer about what the dimensions should be. Similar interactions happened with several welders in this community. There was no language barrier in this case (since the engineer was fluent in the local language), but there was a cultural barrier. In the engineers' work-culture, orthogonal view drawings are the standard, clearest way to present a part.

With these local manufacturers, the drawings were a source of miscommunication because they are not a conventional part of the work-culture in that area. Engineers working in the developing world must be willing to adapt to the conventions of their manufacturing partners.

3.4.5 Pitfall 5: Lacking skills or expertise for a specific project

In 5.6% of the statements, the pitfall was that engineers were working outside of their skills or expertise. When engineers enter a developing community, they are typically seen as problem solvers. While engineers are indeed excellent problems solvers, it is not true that every engineer has the skills to solve all the problems a community may face. Engineers should be careful to balance their desire to be helpful to resource-poor communities with a knowledge of the limitations of their own skills and expertise.

Examples of Pitfall 5

Many of the cases reviewed reported on the difficulties of program evaluation, which is the assessment of the impact a program has had on the community. While program evaluation is certainly important, the engineers on the team are typically not trained to perform this evaluation. In one case, an engineer pointed out that the problem their organization is trying to solve is part of a complex system that has many factors affecting it. When trying to evaluate how well a program solves a problem, it can be difficult to determine whether an improvement was, in fact, made because of the program or if there was another factor that resulted in the improvement [282]. Engineers are typically not well trained in evaluation but other professionals, such as social scientists, do have this training. Engineers could either seek training from these professionals before attempting to evaluate a program, or have these professional conduct the evaluation.

One specific example of this was reported in a case from an agricultural school in Ghana. An engineer working with the school was asked to evaluate a new program. The program appeared to be quite successful and if she could provide some data about how successful it was, they would be able to attract donor funding to expand the program to other schools. The engineer conducted several interviews to collect qualitative data about how the program affected individual's lives, but she also wanted to conduct a survey to gather more quantitative evidence. She designed a survey using a Likert scale and began collecting data. She reports: "Unfortunately, after several weeks of

surveying, I realized I could not use the results in any meaningful way. This was because I had not designed the surveys properly, nor had I realized how difficult it would be to rigorously measure the Likert scale results.” She later stated that she failed to devote the time needed to design a useful survey and failed to seek out experts who could have helped her. Because the information she had collected was not rigorous enough for quantitative analysis, she missed an opportunity to have donors help scale the program and provide greater impact [283]. The engineer in this case could have increased impact by either seeking out training on survey design or by leaving the evaluation to another professional who had the proper training and experience.

3.4.6 Pitfall 6: Miscommunicating or failing to develop trust with local stakeholders

In 4.9% of the statements, the pitfall can be attributed to miscommunication or failure to develop trust with local stakeholders. Building strong relationships can be difficult in unfamiliar cultures but these relationships have a significant impact on the outcomes of projects in developing communities.

Examples of Pitfall 6

In one case, an engineer pointed out that keeping the incentives of each stakeholder clearly aligned can lead to greater impact. He also pointed out that a focus on building relationships and trust is needed to work effectively in a community [274].

An example of miscommunication and lack of trust was shared by an engineer working in the Philippines. It was her responsibility to transition leadership of a program from EWB Canada volunteers to a local government bureau but was told that their workers were too busy to take on the management of another project. To solve the problem, she arranged funding from EWB Canada for the local bureau to hire an additional worker who would lead the program. With this arrangement, EWB Canada would pay the workers salary for one year and if the project was a success, the bureau would continue to pay the salary in future years. The bureau accepted and an additional worker was hired. As the worker began, there was miscommunication about who the worker should report to. While she was officially working for the local government, she was being paid by EWB Canada and this arrangement caused her to question which organizations protocol

should be followed. In failing to follow the protocol of the local government, the worker lost the trust of her employer.

While reflecting on this experience, the engineer recognized that having the worker be paid by one organization but reporting to another made it difficult to keep incentives aligned and to promote trust between stakeholders. She also said, I didnt really trust that my partner [the bureau] would figure out a way to continue the project in my absence so I forced a solution on them [284]. This lack of trust between stakeholders can seriously affect the sustainability and impact of projects in the developing world.

3.4.7 Pitfall 7: Forgetting that communities change over time between field visits

In 2.8% of the statements, engineers specifically mentioned that they didn't consider how communities would change over time and this affected the sustainability of the projects they were working on. While 2.8% is not a very large portion, it is the author's experience that this pitfall affects projects that continue over several years more than the engineers involved typically recognize.

Examples of Pitfall 7

In one case, an engineer was attempting to place a short-term volunteer in a community to collect information about their District Water and Sanitation Team so that they could help support and improve the Team's activities. He considered the various districts they had worked in over the past few years and chose the one he thought was best. This district was one that they had worked in several years ago but that they had not had volunteers in for the previous 2 years. The new volunteer was placed there but after a few weeks, it became clear that the volunteer would not be able to collect the information needed in this district because the key people they had worked with in the past were no longer in this community. This engineer said that "through this failure, our team now recognizes that districts and communities are dynamic and change over time, and that the process by which we select where to work must reflect this" [285].

3.5 Design for the Developing World Canvas

In this section, a visual tool is introduced to help design teams avoid the pitfalls described in the previous section. The tool is called the Design for the Developing World Canvas, as shown in Figure 3.1 and is loosely based on the Business Model Canvas [50]. The canvas presented here differs from the Business Model Canvas in two important ways: First, it was created specifically for the development of manufactured products (not the development of businesses), and second, it was created specifically in response to the 7 pitfalls described in the previous section. In this way the canvas is customized for designing products for the developing world.

Generally, the purpose of this canvas is to help design teams periodically evaluate their progress in advancing the design while avoiding the pitfalls. Using the canvas to prepare for, conduct, or follow up on a design review is particularly valuable since the canvas deals with high-level interdisciplinary items that are often the focus of design reviews. The canvas is a valuable tool for a range of project scopes, from planning preliminary field studies for collecting customer feedback to planning for the entire life cycle of the product. When using the canvas, the team should identify the scope (or subscope) of the project that will be focused on while using the canvas so that it can lead to appropriate decisions.

It is worth noting that the canvas does not simply articulate the pitfalls and encourage the team to consider them. Instead, the canvas emphasizes key facets of product development that should be considered to avoid the pitfalls. It helps the team see the weakest facets of the product development so they can take action to strengthen them.

By strategy, the canvas is *explicitly* linked to the product development process and *implicitly* linked to the 7 pitfalls. To understand why the authors choose an implicit link to the pitfalls, it is valuable to recognize that all canvases are framed with a *progression* focus, where each part of the canvas is included to help the team consider essential things that should be put in place to progress forward. In contrast, all of the pitfalls presented in Section 3.4 are derived from the study of failure and are expressed as things that should not be done. To fit naturally into the traditional framework for canvases and to be a desirable tool that complements the teams forward progression, the canvas emphasizes design progression – not pitfall avoidance.

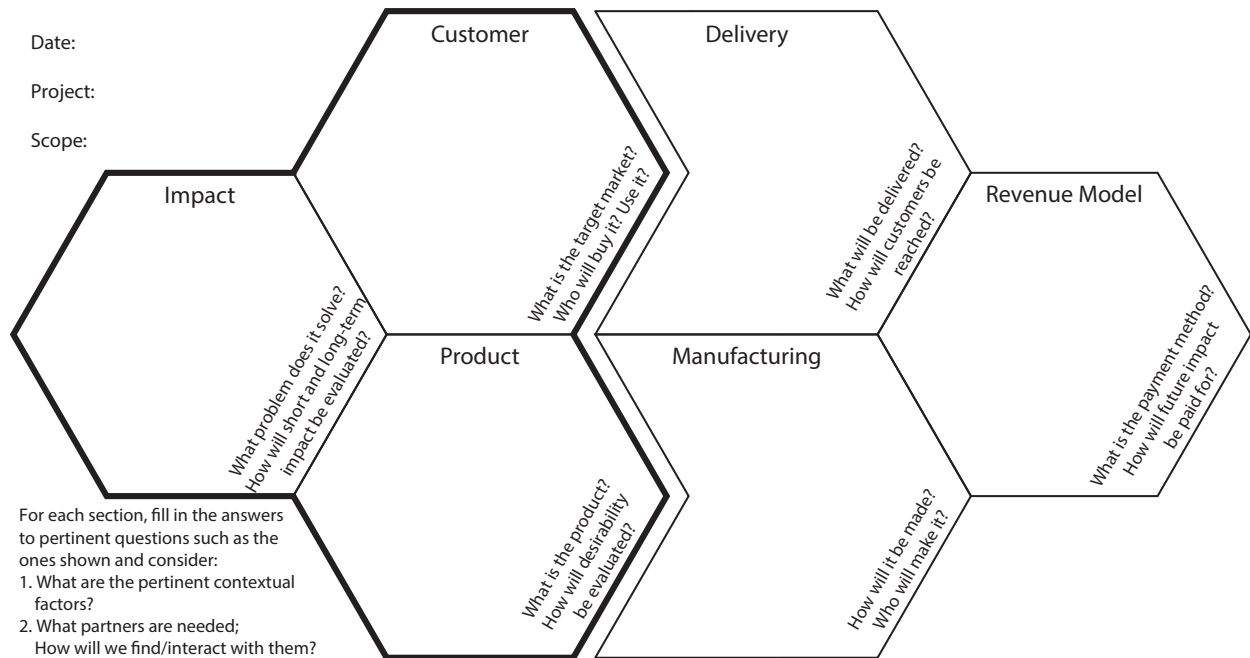


Figure 3.1: The Design for the Developing World Canvas. Each section of the canvas represents an essential part of product development that if thoughtfully considered will help design teams avoid common pitfalls of designing for resource-poor individuals.

Simply having each section of the canvas filled in will not benefit the design team. The value of the canvas is the discussion it will facilitate within the design team. It is the thoughtful discussion and deliberate decision making that will allow the team to avoid the common pitfalls.

To introduce the canvas, a discussion of its structure is provided, followed by a description of each of the sections. How the canvas helps design teams avoid each of the pitfalls is then described.

3.5.1 Structure of the Canvas

The canvas consists of 6 sections purposefully arranged as shown in Figure 3.1. Each section represents a key facet of product development that, if considered periodically, can be used to avoid the pitfalls described in Section 3.4. These facets are Impact, Customer, Product, Delivery, Manufacturing, and Revenue Model. For each section, pertinent questions, such as those provided on the canvas, can be answered by the team in the space provided. Each section of the canvas

will have some influence on each of the other sections; this layout was chosen to show the key interdependencies.

The 3 sections on the left-hand side – Customer, Product, and Impact – are outlined in bold because they are the core of the canvas. These sections should be the first to receive the design team’s attention and are highly dependent on each other. While the design team can start with any of these 3 sections, decisions made for any one of these 3 will affect the possibilities available for the other 2. After questions related to the 3 core sections have been answered, the design team can move to the remaining sections on the right-hand side of the canvas.

The Delivery section is closely related to the Customer section and is therefore positioned next to it in the canvas to emphasize this relationship. To illustrate the close connection, assume the target market is rural farmers; the delivery may require local agents who visit the homes of the farmers to offer the product. Alternatively, if the target market is an urban population, a storefront on a main street may be a more appropriate delivery method. The target market will affect the choice of distribution system.

The Manufacturing section is placed next to the Product section because of the dependency they have on each other. Decisions about the type of product being designed, the materials that will be used, etc. will have a significant impact on where the product is manufactured and what manufacturing processes will be required. The manufacturing processes available locally may also affect the design of the product.

The Revenue Model section is closest to the Delivery and Manufacturing sections because they will have a noticeable effect on the profit generated or lost by the manufactured product. The revenue model will also be affected by and will affect the other sections of the canvas.

In this section of this chapter, each part of the canvas and how to use it is discussed. Following that discussion, the ways the canvas helps design teams avoid each pitfall is outlined.

3.5.2 General Considerations: Contextual Factors and Partners

For each of the sections in the canvas, the design team should consider the contextual factors that are pertinent to that section. For clarity, we define contextual factors to be facts, circumstances, or other influences that shape the customer’s environment. These contextual factors are not likely to be well understood at the beginning of a project, but will develop over time as the

team seeks to learn more about the customer, the community, and the problem being solved. The HCD Toolkit [61] contains many design methods that can be used to collect this information in a developing world setting and Fuge and Agogino [286] offer suggestions for the circumstances where each of these methods is particularly useful and appropriate. Ideally, members of the team would be immersed in the context and perform field studies to better understand the context as they design the product. When this is not possible, the team can work with partners and interact with customers to deepen their understanding of the context. This understanding will help the team avoid each of the pitfalls because as the team better understands the context, they will be more capable of making design decisions that are appropriate for that context. When the design decisions are appropriate for the context, the capacity for impact is much higher.

Each of the sections in the canvas is likely to require a partner to have sustained impact. These partners may be organizations, businesses, manufacturers, or individuals that help the design team meet their objectives for that particular section of the canvas. The design team should go through each section and consider who they will partner with and how they will interact with that partner. Other researchers, including Zimoch et al., have found that having partners greatly increases the impact of their products [287]. Establishing responsibilities is an important part of interacting effectively. Carefully selecting these partners will allow the team to have a longer-term impact than if the team tries to complete each part of the canvas on its own.

3.5.3 Impact

In this section, the design team should clearly articulate the impact they intend the product to have. Depending on the goals of the team, they can focus on any combination of social impact, economic impact, and/or environmental impact. Pease et al. suggest developing an *impact hypothesis* [41]. Teams should write about the impact they intend to have in this area on the canvas. The design team should use this section to answer questions including: What problem does the product solve? How will impact be evaluated?

3.5.4 Customer

This section describes the segment of the market that will both be interested in and benefit from the product. Having a very specific target market will allow the design team to determine the needs of the resource-poor individuals in that target market and design a product that specifically meets those needs.

In this area on the canvas, teams should state what their target market is. If the team has not yet decided on a target market to pursue, they should list the candidates so that they can make a decision as a team or leave the area blank as an indication that they need to discuss this section again when there is more information that will help them make a decision. Note that for some products, there may be more than one target market [288]. In other cases, the person who purchases the product may be different from the person who actually uses it. For example, an NGO may purchase the product and distribute it to resource-poor individuals. If this is the case, the design team should be aware of how this will affect the product development.

In this section, the design team should answer questions such as: What is the target market? Who will buy it? Who will use it? They should also develop and answer any other questions that are specific and pertinent to their project.

3.5.5 Product

In the product section of the canvas, the team will describe the basic product they are designing and how they plan to evaluate the product's desirability. As with all other sections of the canvas, the team will also describe the pertinent contextual factors and needed partnerships, as well as how they plan to find or interact with those partners. The purpose of this part of the canvas is to help the team focus on what is being designed and how it serves the customer and leads to the intended impact.

While most design teams will not need a canvas to encourage deliberate and thoughtful discussions about the product itself, the canvas will help the team recognize that the product is only one part of a larger system designed to have impact. To complete the product section, the team should answer questions such as these while considering other parts of the canvas: What is the product? How will desirability be measured? Note that *desirability* in this case generally refers to

product-specific performance. Ideally, the product-specific performance measures will be clearly related to, but distinct from, the impact section of the canvas. A clear relationship between the two allows the design team to focus on the product, while understanding how changes to the product affect the overall impact. For example, Johnson and Bryden recently developed product-specific safety measures that ultimately connect to the overall impact of their designs in the developing world [289].

Green et al. [60] present a method that can be used to help engineers collect contextual information related to customer needs. This method consists of 5 steps: 1. Identify relevant contextual factors, 2. Generate list of contextual questions to be answered, 3. Gather customer needs and answer contextual questions, 4. Aggregate customer needs into a weighted list, 5. Form context scenario(s) using the answers to contextual questions. This method can be used to help the team effectively discover needs that will determine the specific requirements for the product.

3.5.6 Delivery

The delivery section describes how the product will get to the customer. Connecting a useful product with interested customers can be difficult, especially in a developing community where infrastructure may be lacking. A well-thought-out delivery method could allow the product to have a greater impact. The delivery of the product can also have a surprisingly significant affect on the cost of the product. This can be further explored in the Revenue Model section. One portion of the delivery that is often neglected is the marketing of the product. Postel et al. note that marketing the product in a way that is accessible to users, however unconventional, leads to greater success [77].

AustinBreneman and Yang [92] present three guidelines for engineers designing products to be sold by microenterprises. The guidelines are: 1. Design for the entrepreneurs business plan, 2. Establish a reliable brand identity, 3. Consider multi-functionality. Microenterprise has proven to be an effective method of distribution in many developing communities. If the team chooses to focus on microenterprise or on income-generating products, these guidelines may be useful to them. AustinBreneman and Yang also point out while designing for microenterprise, the design team may have two customers – the end-user as well as the micro-entrepreneur. When filling

in the Customer section of the canvas, the team may choose to have one or more target markets (customers), as long as each is clearly identified.

In this area, the team should write the details of the delivery plan. The design team should answer questions related to: What will be delivered? How will customers be reached?

3.5.7 Manufacturing

This section describes the team's manufacturing strategy for the product. This potentially involves several different suppliers and manufacturing processes. Nevertheless, the team should list sources for the different parts of the product, being careful to align process capability with the needed part. The design team should consider the manufacturing location that is most appropriate for the product. Some teams may choose to have each part made locally in an effort to support the local economy. Other teams may choose to manufacture the product in another location and import it to their customers as a way to capitalize on the economies of scale. Some teams will have a combination of the two. The design team should choose whatever strategy is most appropriate for their specific project.

As an additional resource – tightly coupled to the manufacturing and product sections of the canvas – a list of design for manufacture and assembly principles has been adapted for use in the developing world and may be useful when selecting a strategy [290].

In this area of the canvas, the team should answer questions related to the manufacturing. For example: How will the product be made? Who will make it? The team should also identify the needed partners and plan interactions with those partners.

3.5.8 Revenue Model

This section describes the financial information the team will need to consider as they make decisions about the other sections in the canvas. At its core, this section requires the team to think about how the impact (far left portion of the canvas) will be paid for now and in the future. This section is described as the *Revenue Model* since it is built on the general assumption that if all entities in the supply chain make money, the impact of the project can be sustained for longer than if they don't [38].

Table 3.3: Link between pitfalls and sections of the canvas

Pitfall	General Considerations	Canvas Section
1. Contextual Knowledge	Context, Partners	Impact, Customer, Product
2. Sustainability	Context, Partners	Impact, Delivery, Revenue Model
3. Customer Needs	Context, Partners	Impact, Customer, Product
4. Manufacturing	Context, Partners	Manufacturing
5. Lacking Expertise	Context, Partners	Impact
6. Miscommunication	Context, Partners	Customer, Delivery
Changes Over Time	Context, Partners	Regular use of the whole canvas

In this section of the canvas, the design team will write the cost to manufacture and deliver the product, the price they intend to sell it for, and any profit margin the team needs to include. The team should consider questions like: What is the revenue strategy? What is the payment method?

The design team may want to consider different payment options. In the authors' experience during pilot tests of new products, resource-poor individuals in many communities are accustomed to paying for more expensive products in installments and are often willing to pay a significantly higher price if they can pay over time. Accepting payments may be logistically complicated for the design team, but it may also increase the product's impact by making it available to a wider range of the target market.

3.5.9 How the Canvas and Pitfalls are Linked

While the link between the canvas and pitfalls is implicit, it is powerful. Table 3.3 shows each pitfall and the sections of the canvas that, if thoughtfully considered, will help the team avoid the pitfalls. The following sections provide further discussion regarding the information found in the table.

Avoiding Pitfall 1

The canvas directly helps teams avoid Pitfall 1: *Lacking the contextual knowledge needed for significant impact* when it prompts the team to consider pertinent contextual factors for each section of the canvas. Identifying pertinent contextual factors as well as the needed partners are general considerations because they apply to each of the sections of the canvas. Partnerships in particular are essential to understanding the context of the community, the problem to be solved, and how the product will help resource-poor individuals.

The impact section of the canvas compels the team to ask what problem the product intends to solve and how its impact will be measured. This helps engineering teams that tend to focus more on the product to not lose track of the intended impact. The canvas also encourages the team to identify their target market and seek a deeper understanding of the customers' context as they explore potential needs and solutions. This understanding will help the team avoid Pitfall 1 because a deeper understanding of the context leads to more contextually appropriate design decisions. Thoughtfully completing the product section of the canvas also helps because it causes the team to discuss what the product is, how its going to be used in a specific context, and how its desirability is going to be evaluated.

Avoiding Pitfall 2

Pitfall 2: *Neglecting to make a plan for or developing partners for long-term sustainability* can also be avoided by using the canvas. For example, when a team carefully considers the impact section of the canvas, the team naturally begins to think about long-term impact and the sustainability they want their product to have in the context its designed for. Whether using the canvas to characterize long or short-term impact, the team will want to choose effective partnerships, knowing that long-term sustainability is unlikely without those external relationships. Partnerships aimed at sustainability will likely be needed in multiple areas of the canvas, such as the delivery and revenue model sections. As the team considers the delivery section of the canvas, mechanisms for delivery can be explicitly chosen to remain in place after the core design team has moved on to other projects. If the revenue model is organized so that it is contextually appropriate and so that

the intended impact can be paid for now and in the future, then the product can be distributed to a greater number of customers in the future.

Avoiding Pitfall 3

As the team thoughtfully uses the canvas, Pitfall 3: *Assuming the needs of the customers being served* can also be avoided. In an interconnected way, the core of the canvas, as outlined in bold, focuses the team on the needs of those being served. For example, the impact section asks the team to articulate what problem is being solved, and how the impact will be measured; the customer section encourages the team to define who would want the product and how they would use it; and the product section requires the team to establish how the desirability of the product will be evaluated. Each of these sections – if conscientiously considered – allows the team to question their assumptions which undoubtedly leads to more accurately discovering the true needs of the target market. The general considerations of context and partners are invaluable to avoiding this pitfall because they help the team recognize that essential information often lies outside of the team’s knowledge base.

Avoiding Pitfall 4

Not making a plan for or developing partners for manufacturing is Pitfall 4. The manufacturing section of the canvas is designed to help the team avoid this pitfall. In this area of the canvas, the team should answer questions related to the manufacturing, such as: How will the product be made? and Who will make it? The team should also identify the needed manufacturing partners and plan the interactions with them. The answers to these questions and reflections on context and partnerships will guide the team to make decisions that help them avoid Pitfall 4.

Avoiding Pitfall 5

Another pitfall that can be avoided using the canvas is Pitfall 5: *Lacking skills or expertise for a specific project*. Specifically, the impact section can help the team thoughtfully decide whether the skills of the team align with the desired impact and the way it will be measured. This

will allow the team see what expertise may be missing and find the appropriate partners with that expertise.

Avoiding Pitfall 6

Pitfall 6: *Miscommunicating or failing to develop trust with local stakeholders* can be avoided as the team carefully plans their interactions with each of the partners they choose. This thoughtful interaction will build trust over time. Trust with customers is also essential for avoiding this pitfall. This begins as the team considers the customer section of the canvas and starts to understand more fully who the customers are and what they need.

Avoiding Pitfall 7

The last pitfall, Pitfall 7: *Forgetting that communities change over time between field visits*, can be avoided by periodically reviewing the canvas throughout the product development process – especially as it relates to a growing understanding of the context and its dynamic nature. The design team should review the canvas on a regular basis as they learn more about the community and learn new information that will affect the various facets of the design as captured in the canvas.

3.6 Case Study in Using the Canvas

3.6.1 Background

The Design for the Developing World Canvas was used to create a cookstove potskirt which is a reconfigurable flue that reduces emissions, fuel used, and time spent cooking traditional meals. The canvas helped the team prepare for a two week early-stage field study to rural Peru, where most people cook over an open fire. The design team consisted of engineers who have worked on a total of 14 design for the developing world projects in the last few years. While it was not practical in this case to have two teams working on the project where one used the canvas and one did not to compare, the team can make comparisons – albeit anecdotally – to previous projects completed without the canvas.

3.6.2 Use of the Canvas

The canvas was used in during a weekly design review for the 5 weeks preceding the field study as well as 3 times during the field study. During the design reviews, a blank canvas was filled out with the canvas from the previous week as a reference. In one-on-one interviews, all members of the team agreed that using the canvas did not feel intrusive and did not feel like an extra activity they had to do apart from the product development. During the first design review using the canvas, the team had information to put in some of the sections but others were blank. As they worked through the canvas each week, they noticed that some of the sections were becoming well defined and they were able to spend most of their time working on the sections that were less defined. Filling out the canvas typically took an hour and the discussion the team had led to a series of tasks to be completed. Each team member was given several tasks at the end to keep the design moving forward. These were reported then on in the following week's meeting, using the sections of the canvas to drive the agenda.

3.6.3 Benefit of Using the Canvas

Compared to the teams previous design for the developing world experiences, using the canvas allowed them to be much more effective at collecting a high quantity and quality of customer feedback on the product, which was the goal of the field study. Using the canvas, the team quickly decided the impact they wanted to have with this field study – at this stage of the product development, the team was most interested in collecting early customer feedback. The discussion facilitated by the canvas helped them see that taking 10-20 sets of potskirts would not be enough, as would have been more consistent with the team's previous developing world projects. The team made the goal to distribute 70 sets of potskirts during the trip. Talking about and deciding on this number affected their choices in other sections of the canvas, for example they knew they could not manufacture this many by themselves so they sought out appropriate manufacturing partners and planned their interaction with them. Also, they wanted to give users time to test the potskirt prototype for several days before the team interviewed them for feedback. This meant that they needed a strong plan for delivery, which the canvas helped them develop. Using this plan, they distributed 66 pairs of potskirts in their first 4 days in the field. Several days later, they were able to

collect feedback from 42 users. The team's discussion while using the canvas helped them allocate resources to match their goals for intended impact.

The members of the team had not had that kind of success in a two week field study before and each member of the team said they felt that the canvas helped them achieve this because it guided them to consider not just the product, but the structure that supports the product as well. Nearly all members of the potskirt team had previously worked on another product that was also tested in Peru. Designed without the canvas, that product was one of the teams most clever mechanical products. Here, the team was very focused on the design and largely neglected the supporting structure. They had only two prototypes which they produced themselves and this represented the majority of their effort. When they arrived in the field, the supporting structure was not in place because the team had not worked to develop it. The team had a difficult time distributing even two prototypes and were not able to collect a useful amount of customer feedback. The members of the potskirt team agreed that had they used the canvas for their earlier projects, significantly different outcomes would have been likely.

3.7 Discussion and Concluding Remarks

Engineers have an important role to play in global development, but face many challenges as they design products for resource-poor individuals. These challenges can cause both experienced and inexperienced engineers to make poor design decisions in a developing world context. In this chapter, the authors reviewed reports of 41 engineering projects in the developing world and identified 7 common pitfalls that engineers encountered. Examples from the reports for each of the pitfalls were given.

After the common pitfalls were identified, the authors presented the Design for the Developing World Canvas as a visual tool to help engineers avoid these pitfalls. Other canvases, such as the Business Model Canvas [50], exist and may be helpful for design teams, but the canvas presented in this chapter was created specifically for engineers designing manufactured products for customers in the developing world. It is particularly useful in this situation because each section represents a key facet of product development that can be easily forgotten in the product-centric environment that often surrounds engineers. As the team considers those facets individually, they will have a more holistic approach to solving problems faced by resource-poor individuals.

The canvas is most valuable when used to prepare for, conduct, or follow up on regular design reviews. When the team answers questions, as prompted by the canvas, a deeper appreciation for the complexity of the problem emerges, encouraging the team to more carefully choose solutions. The canvas can be adequately completed by an individual in about 30 minutes, or in a team setting in about 60 minutes.

The team may also use the canvas *after* a project has been completed to evaluate a project – especially a failed project. Filling out the canvas at this point will help expose the strengths and weaknesses in the team’s approach, which can clearly lead to future improvements and greater impact.

A strong message of this chapter is that simply having the canvas filled out for a project has little value for the design team. The practical value of the canvas is in the discussions it facilitates and the awareness of the areas being or not being addressed by the team. Having a visual tool to represent each of the 6 sections allows the team to consider and discuss each section with relative ease. It shows the team the weaker areas of the product development and can help the design team understand the next actions to take or the next questions to answer. This will guide the team to work on the next most important aspects of the design. It is natural when using the canvas to assign responsibility and resources for completing essential tasks.

Ultimately, the process of regularly using this canvas allows the design team to thoughtfully consider and make deliberate decisions for each of the facets of product development related to the 7 common pitfalls. This leads the team to solutions that avoid those pitfalls, and allows them to have greater potential for long-term impact.

CHAPTER 4. VILLAGE DRILL: A CASE STUDY IN ENGINEERING FOR GLOBAL DEVELOPMENT WITH FIVE YEARS OF DATA POST MARKET-INTRODUCTION

4.1 Chapter Summary

This chapter presents a case study in engineering for global development. It introduces the Village Drill, which is an engineered product that has – five years after its introduction to the market – enabled hundreds of thousands of people across 15 countries and three continents to have access to clean water. The Village Drill creates a 15 cm (6 inch) borehole as deep as 76 m (250 feet) to reach groundwater suitable for drinking. The case study presents facts for the actual development and sustaining and are unaltered for the purpose of publication. This approach provides the reader with a realistic view of the development time, testing conditions, fundraising, and the work needed to sustain the drill through five years of sales and distribution. The purpose of the case study is to provide sufficient and frank data about a real project so as to promote discussion, critique, and other evaluations that will lead to new developments that inspire and inform successful engineering for global development. As part of the case, the chapter describes six fundamental items; the product, the customer, the impact, the manufacturing, the delivery, and the revenue model of the drill.

4.2 Engineering for Global Development and the Need for Case Studies

Engineering for global development is an interdisciplinary practice that aims to improve the quality of life of underserved communities worldwide through the design and delivery of technology-based solutions [291]. Participation in engineering for global development is often motivated by societal altruism, a desire to tap into new global markets, and/or interest in advancing technology to extreme limits [292].

While a growing number of individuals are motivated to participate in engineering for global development, it has proven to be difficult to do it successfully and sustainably [43], [293]. The difficulty is not yet fully understood, but is influenced by large physical distances and cultural

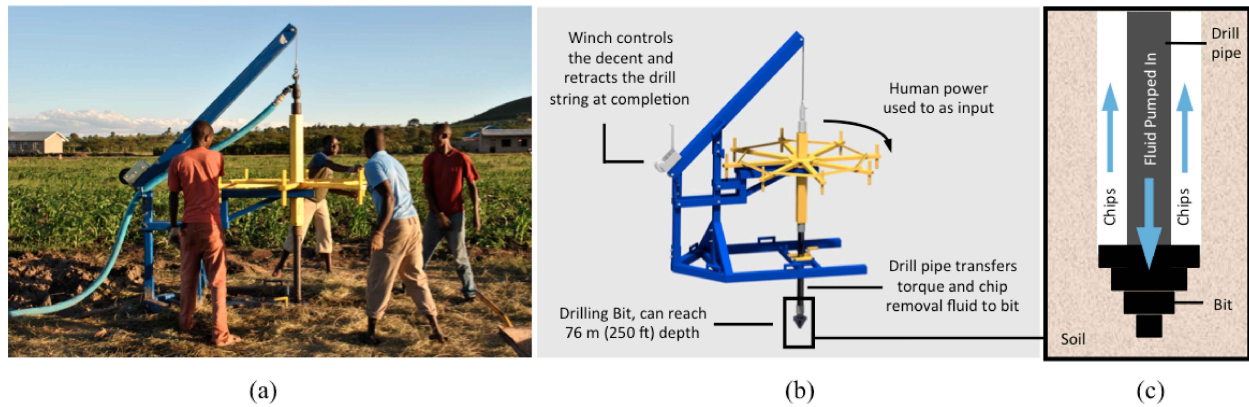


Figure 4.1: Village Drill: (a) in use in Tanzania, (b) description of basic function, (c) detail of drilling bit and chip removal.

differences between engineers and end-users, stakeholder imbalance [294], and the realities of high experimental costs in highly uncertain environments [295].

Some engineering work is beginning to appear in the literature that can guide the general process of engineering for global development [42], [92], [296]–[298], but it is realistic to acknowledge that the current state of knowledge is in its infancy. One specific thing missing from the literature are case studies with years of data showing how engineering efforts eventually lead to positive impact. Also missing are descriptions of what happens between initial in-field product development experiments and scaling up to reach large numbers of people. Frank and unembellished case studies of this nature have the potential to inspire and inform successful engineering for global development.

The purpose of this chapter is to present the Village Drill as a case study.

It presents facts for the actual development and sustaining and are unaltered for the purpose of publication. We believe that this approach will provide the reader with a realistic view of the development time, testing conditions, fundraising and cashflow, sustaining, sales, and distribution for a technical product engineered for a developing world setting.

4.3 The Village Drill Case Study

The Village Drill is a human powered machine that creates boreholes for water wells. Figure 4.1 conveys the basic drill functionality. As shown, the drill is operated by spinning the input

Table 4.1: Village Drill Measures After 5 Years ($n_t = 65$)

Productivity Measures	
Drills produced in total (n_d)	41
Drills in service (n_{d_s}) during time period 65* ($n_t = 65$)	34
Productive boreholes drilled in total (n_{b_t})	761
Productive boreholes drilled (n_{b_p}) during $n_t = 65$	31
Primary Impact Measures	
Wells in service (n_{w_s}) during $n_t = 65$	453
People being served (drinking) (n_{pops}) during $n_t = 65$	188,176
Unique people served (drinking) in total ($n_{pops_{max}}$)	316,281
People-months of water provided in total (n_{pmws})	4,129,945
Secondary Impact Measures	
Countries using the Village Drill during $n_t = 65$	15
Acres irrigated (n_{as}) during $n_t = 65$	109
Acres-months of irrigation provided in total (n_{amws})	2,385
People employed (on drills) (n_{pope}) during $n_t = 65$	238
Months of employment created (on drills) (n_{pme}) in total	5,838
Total income through fund raising (USD)	\$448,375
Total income through drill invoices (USD)	\$658,500

* Time period 65 is the last month evaluated before publication

wheel (yellow), while lowering the drill string in a controlled way using the hand-operated winch. The drill string is an assembled length of 6 cm (2.5 in) diameter drill pipes and a 15 cm (6 in) diameter bit. The drill is designed to reach water up to 76 meters (250 ft) below the surface. Chips from the drilling are removed as a mixture of water and commercial-grade bentonite is pumped down the drill pipe through the bit. Chips are brought back to the surface by the mixture through the annulus around the pipe. At the surface, the chips are removed from the fluid mixture in a small settling pond and the fluid is repumped into the drill string.

The Village Drill belongs to WHOlives.org – a non-profit organization that commissioned Brigham Young University (BYU) to design and test the Village Drill. The key impact measures for the drill, representing its full 5-year history, are presented in Table 4.1. Note that the data in this table does not account for uncertainty and is therefore deterministic. The deterministic analysis is described in Section 4.3.5 and the effects of uncertainty are accounted for in Section 4.3.9.

After providing a brief introduction to the case study (Section 4.3.1) and its timeline (Section 4.3.2), six fundamental parts of the project are then discussed: product, customer, impact, manufacturing, delivery, and revenue model. These six parts were chosen to be consistent with

the discussions laid out in Wood and Mattson [43] about avoiding failure in a developing world setting.

4.3.1 Case Study Introduction

Providing access to clean water is one of the world's greatest engineering challenges. It is one of the 14 grand challenges of the 21st century as defined by the National Academy of Engineering [299]. Even so, this challenge can be easily overlooked since most of the world's engineers have continuous uninterrupted access to clean water, and are therefore far removed from this challenge and its effects. The water disparity between developed and developing parts of the world is significant. For example most estimates put water consumption in the US at 303-379 liters (80-100 gallons) per day per person, while water for domestic use in Rwanda is 9.11 liters (2.41 gallons) per person per day. To put this into perspective, the amount of daily water available per person in Rwanda is consumed in 73 seconds using a low flow EPA certified WaterSense shower head [300].

This case study is focused on accessing drinkable ground water. There are three broad challenges associated with accessing this water. They are: (i) knowing *where* to drill a borehole that will access extractable ground water, (ii) knowing *how* to cost-effectively drill a borehole to reach the water, and (iii) knowing how to prepare and maintain the system that goes into the borehole to extract the water. While all of these challenges were faced and dealt with during the history of the Village Drill, this case study focuses specifically on the second item – how to cost-effectively drill a borehole.

There are a number of ways to produce boreholes to access drinkable ground water. The most common is to use a professional scale well-drilling rig. These systems can drill deep holes (hundreds of meters) through rock relatively quickly. Creating a borehole with a well drilling rig in Africa can cost between \$15,000 and \$25,000 USD. Because of their large size, these drilling rigs cannot access most villages or cannot drill a hole in a desirable location such as in the center of a small community. These drawbacks make well drilling rigs financially and physically inaccessible to a large number of people.

When drilling rigs are inaccessible, two alternative approaches are often pursued: Hand auguring and sludging. Hardware for these approaches are inexpensive, but are slow and laborious

to use, are restricted to relatively soft soils, and are limited in depth-of-cut. The simplest forms are limited to creating holes approximately 10 meters deep. The most advanced forms can reach depths of 100 meters. The inexpensive nature of these devices has improved access to ground water for many people. Both of these alternative methods are suitable in loose soils and with adaptation can be used in more diverse soil types. However, neither is well-suited for medium to hard rocks formations. The Village Drill was created to compete in between the well drilling rig and hand auguring/sludging space.

The Village Drill case study has five fundamental components at its foundation. The articulation of these components is consistent with accepted case study research methodology [301]. For this case study, they are:

1. The case study's question: What impact has the Village Drill had on water-poor individuals?
2. The case study's propositions: The Village Drill has served people in need of drinking and irrigation water. The Village Drill has given employment to Village Drill operators.
3. The case study's subject of analysis: The Village Drill.
4. The logic linking case study's data to the proposition: The Village Drill produces boreholes. Not all boreholes successfully lead to water. Those that do are fitted with a pump and become a functioning well. Water-poor individuals access clean water via the well. Not all wells get maintained, some fall out of service. Some individuals who gained access to water have lost it when wells are not serviced. Each borehole drilled employs a set of drill operators.
5. The criteria for evaluation: In any impact analysis, such as the one offered in this chapter, it would be easy to intentionally or unintentionally overstate the impact achieved. To guard against this, we use two layers of protection in this chapter. Both are described in more detail below; the first is that we have chosen to use the most conservative parameter values that we have evidence for in the impact analysis. Second, we have carried out a detailed uncertainty analysis and express the impact achieved in terms of confidence intervals greater than 97%.

4.3.2 Village Drill Timeline

A detailed timeline is provided in Figure 4.2.

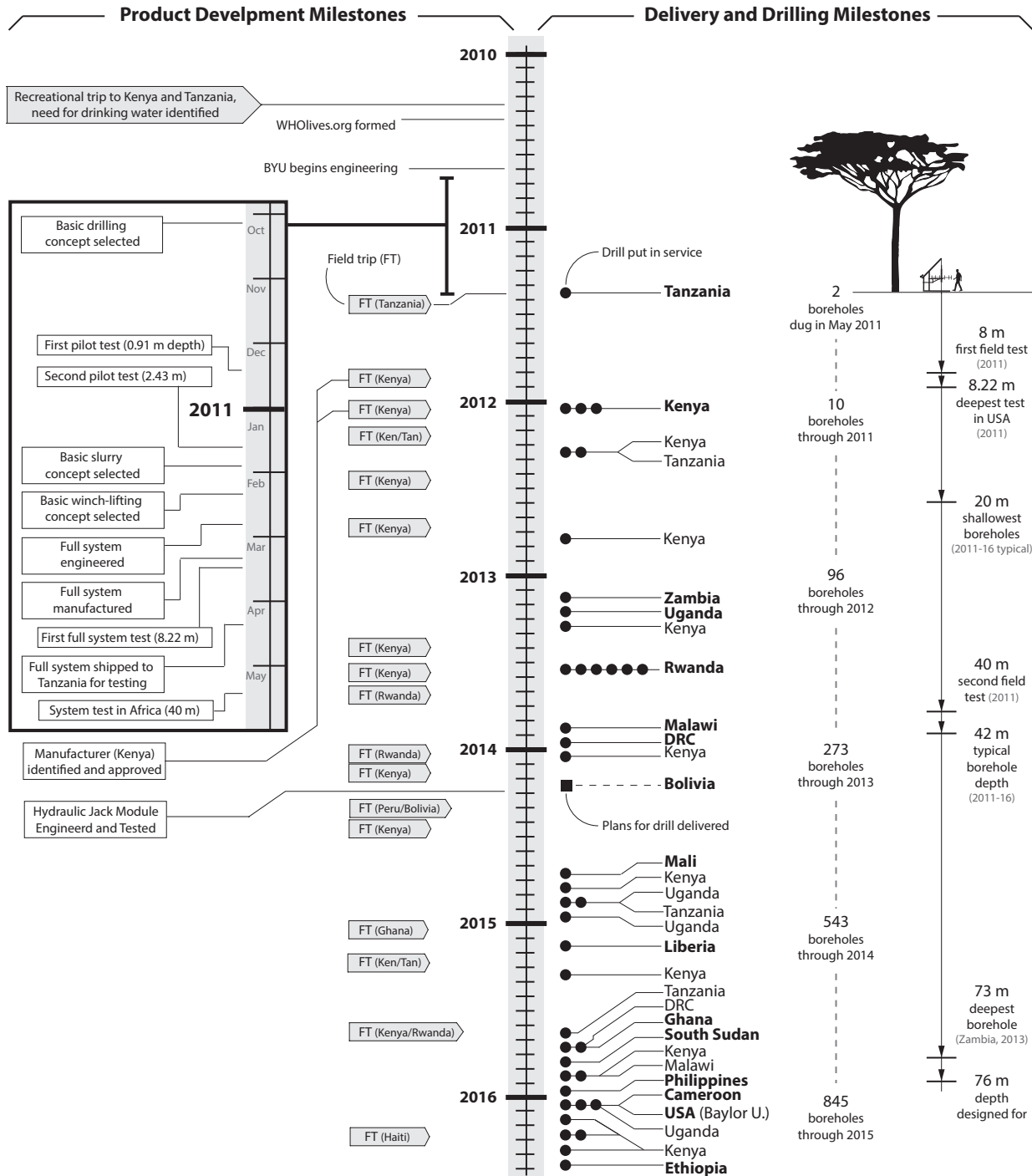


Figure 4.2: Timeline for product development and delivery/drilling milestones.

The left half of the figure shows product development milestones, while the right half shows delivery and drilling milestones. Notice that the solid black circles represent drills that entered service, and that the gray arrow boxes represent field trips. For convenience of seeing the data in one figure, the data shown on the extreme right side of the image indicates borehole depth to scale and is unrelated to time – except for the parenthetical note of when those depths were achieved.

Several valuable pieces of information are found in the figure. For example, a large portion of the product development time spent by BYU (5-6 months) was in developing a system concept that would meet WHOlives.org's and end-users' needs. Once that system concept was chosen and its parts were tested, the detailed engineering of the Village Drill was carried out relatively quickly (2-3 weeks).

Another observation from the data presented in the figure is that WHOlives.org focused for approximately two years on just two countries (Kenya and Tanzania) before expanding out to 13 additional countries in the three years that followed. It's also worth acknowledging the 17 field trips that were required to carry out the project during the past five years. More about the data shown in Figure 4.2 is presented in the final section of this chapter.

4.3.3 Product

The Village Drill was designed by two of the authors (Mattson and Renouard) together with multiple students (listed in the acknowledgements). The basic system is shown and described in Figures 4.1 and 4.3. The drill was designed to use as much proven well-drilling technology as possible, while being human powered as much as possible. This strategy was chosen to reduce technical risk, and due to the simple nature of the design, reduce cost and complexity – thus making the drill more desirable and accessible, and therefore reduce market risk.

In the early stages of product development the most important customer needs were identified as:

1. The drill reaches potable water beyond 30 m (100 ft)
2. The drill cuts through rock
3. The drill uses existing drill bits

4. The drill seals borehole sides to prevent cave-in
5. The drill removes cuttings from the borehole
6. The drill works at an efficient speed
7. The drill uses only human power to operate
8. The drill is portable
9. The drill is comfortable to operate

These were translated (using the concepts of quality function deployment [104]) into multiple performance measures including; borehole depth, downward drilling force, applied torque to drill pipe, weight of heaviest subassembly, etc.

Designed to meet these needs, the Village Drill fills a unique spot in the market; for relatively shallow borehole depths (<76 meters), the drill mimics a large scale drilling rig at much lower financial cost and requires significantly less technical knowledge to operate.

The Village Drill has four major subsystems, three of which are shown in Figure 4.3; the structure, the drill string, and the input wheel. The fourth subsystem is the pumping system and is not shown. The Village Drill is designed to come apart into the pieces shown in Figure 4.3, and be transported to the job site in a small pick-up truck, cart, or by hand for up to 1 km distance.

The basic concept/configuration of the Village Drill was chosen for specific reasons: (i) The wheel was oriented horizontally at an ergonomic height to make the best use of biomechanics. The operators remain stationary, while using their upper body to push the wheel in a clockwise fashion. The wheel acts as a large flywheel that keeps the wheel spinning with minimal strain on the body. The winch plays an essential role in the functionality of the Village Drill; it prevents the drill string from wedging itself into the soil. When wedged into soft soils the drill string cannot be turned sustainably by human power. The winch also retracts the drill pipe once ground water is reached. The wheel support attaches to the vertical part of the structure to leave as much room around and under the wheel as possible to improve safety of operation and ease of adding pipe segments to the drill string. The wheel, wheel support, Kelly bar, and swivel are designed to be easily removed from the structure once water is reached. The structure is then used as a hoist to

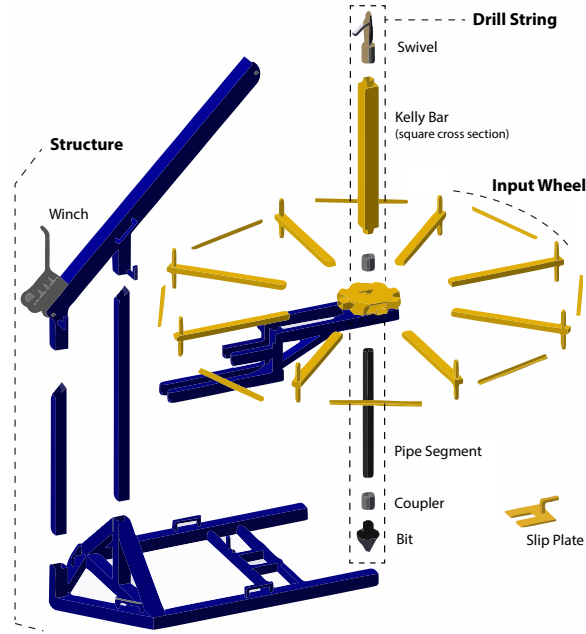


Figure 4.3: The major subsystems and parts of the Village Drill. The structure divides into 5 parts; the base, the boom, the wheel support, and two vertically oriented beams to give the boom height. The input wheel has a center hub (welded) with eight spokes that extend from it and are secured by eight cross members. The drill string includes the swivel, Kelly bar, and many short (meter-long) pipe segments and couplers that are added to the drill string as the borehole deepens. The Village Drill disassembles into the pieces shown for transport to and from the job site.

remove the drill string, two pipe segments at a time. The design of the pipe couplers and the drill base are such that a plate (shown as slip plate in Figure 4.3) can be slipped around the drill pipe and under the coupler to hold the weight of the drill string while the pipes above it are removed and is no longer supported by the winch. The slip plate rests on the cross members shown between the legs of the base. These specific innovative features were chosen to rectify problems identified in the pilot tests performed in the US (in late 2010 and early 2011, as shown in Figure 4.2).

Two other parts of the concept/configuration are essential to the Village Drill and are strategically chosen from existing well-drilling technology. The first is the interface between the input wheel and the drill string. The technology used is termed a *Kelly bar*. The Kelly bar slips through a square opening in the input wheel as shown in Figure 4.3. This allows the wheel to apply a torque to the Kelly bar, while simultaneously allowing the bar to descend into the borehole as the hole deepens. The other parts of the drill string are also chosen from existing technology; the drill bit, the drill pipe (though shortened to 1 meter sections), and the swivel.

The second major sub-system chosen from existing technology is the pumping system. Existing rig-based drills pump a water/bentinite mixture through the drill pipe as shown in Figure 4.1(c). The purpose of this mixture is to remove the cutting chips and seal the borehole. The basic concept for the Village Drill (in this regard) is equivalent to that of existing drilling technology. For the Village Drill, a small petrol-powered slurry pump is used to pump the water/bentinite mixture down the drill pipe while it is being spun by the operators.

After the initial testing of the Village Drill in Tanzania (2011), and making minor changes, relatively few modifications have been made to the Village Drill. Three system modules, however, were added over time. In 2011, weight collars were designed and added to the Village Drill system. These collars slip over the first drill pipe (closest to bit). The bit keeps the collar from slipping off. The collar provides additional downward force for drilling through rock. In 2013, additional drill bits were added to the Village Drill system. Originally the system only included a drag bit. Later it included both a drag bit and a tri-cone bit. In 2013, WHOlives.org engaged BYU to design a module to apply more downward pressure to drill through rock. The module attaches to the Village Drill boom and uses a hand-operated hydraulic jack to apply a large downward force, while the drill itself is secured with earth ties.

4.3.4 Customer

When the Village Drill was being developed, it was intended to be used as a microbusiness, where a local person would rent or buy the drill and then increase their income by drilling wells for other people. This is still one part of the long term goal, but purchasing a Village Drill is a massive investment resulting in all of the manufactured drills having been purchased by either non-governmental organizations (NGOs) or wealthy individuals in the developed world who donated them for use in developing communities. The primary customers for the Village Drill are NGOs. In the initial years of distribution, these NGOs were based primarily in Africa. In the subsequent years however WHOlives.org has started to serve NGOs in South America, and Asia as well. Customers pay \$18,000 USD for a Village Drill and training. This includes bits, drill pipe, couplers, and everything needed to drill.

WHOlives.org owns and operates 4 of the 41 drills that have been produced. Using these 4 drills, WHOlives.org drills boreholes for those who are not in the market for a Village Drill but

are in the market for a borehole. These borehole customers range from individuals, to schools, to villages, to farmers. These customers pay approximately \$4,000 USD for a productive borehole with a hand pump installed.

4.3.5 Impact

Five years after introducing the drill to the market, WHOlives.org and BYU worked closely together to develop a meaningful set of impact models for the Village Drill. These models were derived and refined using data and experience from WHOlives.org's founder, its African business development leader and its African well drilling teams. The models presented here are centered on the measures deemed most important to WHOlives.org. We present them as part of the case study so as to make it clear how each impact measure was calculated, what parameters were involved, and how they were chosen. This coupled with the raw data provided at the end of this chapter allows others to use this case study as the basis for additional studies.

Nomenclature

Productivity Measures:

- n_d Number of drills produced in total
 $n_{d_{si}}$ Number of drills in service, for time period i .
 n_{b_t} Number of productive boreholes drilled in total
 $n_{b_{pi}}$ Number of productive boreholes drilled during time period i .

Primary Impact Measures:

- $n_{w_{si}}$ Number of wells in service during time period i .
 $n_{pop_{si}}$ Number of people served (drinking) during time period i .
 $n_{pop_{s_{max}}}$ Unique people served (drinking) in total
 n_{pmws} Number of people-months of drinking water provided in total

Secondary Impact Measures:

- n_{asi} Number of acres served (irrigation) during time period i .
 $n_{pop_{ei}}$ Number of people employed operating drills during time period i .

n_{amws} Number of acre-months of irrigation water served in total
 n_{pme} Number of people-months of employment created in total (operating drills)

Input Parameters:

$n_{d_{osi}}$ Number of drills out of service during time period i .
 n_{d_r} Number of drills retired in total
 $n_{b_{pm}}$ Number of boreholes (average) per month a drill creates
 n_t Number of months past since start of project
 n_{hub} Number of people (average) served by borehole at village center (hub)
 n_{rim} Number of people (average) served by borehole in village outskirts (rim)
 n_{apw} Number of acres (average) irrigated per well
 n_{popepd} Number of people employed per drill

f_{hub} Fraction of wells serving village centers (hub)
 f_{rim} Fraction of wells serving village outskirts (rim)
 f_a Fraction of wells used to irrigate acreage

l_{mbf} Life expectancy (in months) of hand pump before first service required
 l_d Life expectancy (in months) of drill

p_{fms} Probability of hand pump receiving first service

Subscript Notation:

$[]_{[]i}$ Indicates $[]_{[]}$ for the i -th time period

Productivity Measures

In this section, we describe productivity measures used to judge WHOlives.org's efforts to use the Village Drill to create productive boreholes. Note that the smallest time increment used to

make these judgements is one month, and that the numbers labeled *total* represent the total sum over the full history of the drill.

The total number of drills produced (n_d) is tracked via drill invoices; the total is listed in Table 4.1. To create realistic measures, we account for the fact that some drills are sitting idle (functional, though not in service) or have been retired from service. Therefore, the number of drills in service for any given month is evaluated as

$$n_{ds} = n_d - n_{dos} - n_{dr} \quad (4.1)$$

The value n_{dos} varies month-to-month and is relatively well-known for all time periods, and the number of retired drills (n_{dr}) is known to be 0. Section 4.3.9 includes an analysis to account for the uncertainty in the model's input parameters, including n_{dos} .

A productive borehole accesses useable water. Only a fraction of the boreholes created are productive (hit water). The number of productive boreholes drilled (n_{bp}) for any time period is calculated as

$$n_{bp} = n_{ds} * n_{bpm} * f_{bp} \quad (4.2)$$

where n_{bpm} is the average number of boreholes drilled per Village Drill per month and f_{bp} is the fraction of boreholes that are productive. For this chapter, these values are estimated for all drills as 1.25 and 0.73, respectively. These values are chosen by examining the work of WHOlives.org's drilling team and then extending to all other NGO drilling teams not operated by WHOlives.org. The total number of productive boreholes created, n_b , is simply the sum of n_{bp} over all time periods.

Primary Impact Measures

While the productivity measures are directly related to the Village Drill, they are a step removed from the intended impact, which is centered on people – not drills. In this section, we present the primary impact measures used to judge the value of the Village Drill.

We assume that each productive borehole is cased and a hand pump is installed to create a well. Hand pumps, however, require servicing to remain functional and only a fraction of the

pumps installed will receive their first service. As a result, the number of wells in service increases when productive boreholes are created, and decreases when wells do not receive their first service. During the initial part of the project, before reaching the expected life (l_{mbf}) of a pump before its first service, the number of wells in service per month can be estimated as

$$n_{ws} = \sum_{i=1}^{n_t} n_{bpi} \quad \text{when } n_t \leq 14 \quad (4.3)$$

where n_t is the number of time periods (months) used in the analysis. For this analysis $n_t = 65$ and $l_{mbf} = 10$. The number 14 is chosen for the inequality because the first borehole was drilled 4 months after the first time period of the analysis. The number 14 is simply the summation of those 4 months and the 10 months representing l_{mbf} . After the initial period of the project, the number of wells in service can be estimated as

$$n_{ws} = \sum_{i=1}^{n_t} n_{bpi} - \sum_{i=1}^{n_t - l_{mbf}} n_{bpi} (1 - p_{fms}) \quad \text{when } n_t > 14 \quad (4.4)$$

where p_{fms} is the probability that a pump will receive its first service at or before the pump life expectancy (l_{mbf}) is reached. Unfortunately, the probability of hand pumps being serviced is globally low – potentially as low as 0.15. Nevertheless, in consultation with WHOlives.org’s drilling teams and considering the WHOlives.org training and support system, we estimate this probability to be 0.4.

Given the number of wells in service, we can calculate the number of people served each month. It is typical to estimate that a well can serve 1000 people. However, to be as realistic as possible, we consider 1000 people to be an upper limit. Instead, informed by the experiences of WHOlives.org, we categorize wells in service as being used in three different ways: (i) to serve a village (drinking) near its center, (ii) to serve a village (drinking) on the outskirts of the village, and (iii) to serve acreage (irrigation). The fraction of wells serving a village center (f_{hub}) is assumed to be 0.78. The fraction serving the outskirts (f_{rim}) to be 0.16, and the fraction irrigating acreage (f_a) to be 0.06. These fractions were chosen by examining the work of WHOlives.org’s drilling team and extending the same fractions to all drilling teams. The number of people served (drinking) per

month is estimated as

$$n_{pops} = n_{ws} (f_{hub} * n_{hub} + f_{rim} * n_{rim}) \quad (4.5)$$

where the estimated number of people served at the village center (n_{hub}) is conservatively chosen as 500, and the number of people served on the outskirts of the village (n_{rim}) is 160 per well.

Given that pumps in service go out-of-service if not maintained, WHOlives.org keeps track of the total number of unique people served (drinking) over all time periods ($n_{pops_{max}}$). Comparing this number to those served in the last time period (n_{pops}) lends insight to the number of people once served who are no longer served.

To value the cumulative effect of time, it is meaningful for WHOlives.org to estimate the total number of people (not unique people) who have had access to a well for at least one month. We call this number *people-months of water provided* (n_{pmws}), and calculate it as

$$n_{pmws} = \sum_{i=1}^{n_t} n_{pops_i} \quad (4.6)$$

Secondary Impact Measures

This section presents additional, secondary impact measures that are important to WHOlives.org.

The number of acres served (irrigation) per month (n_{as}) is calculated as

$$n_{as} = n_{ws} * f_a * n_{apw} \quad (4.7)$$

where f_a is the fraction of wells used for irrigating acreage, and n_{apw} is the average number of acres irrigated per well. The latter is set to 4 acres per well as determined by WHOlives.org's director of drilling and installation in Kenya.

Cumulatively, the total number of acre-months of water provided (acres that have received one month of water) is simply the sum of n_{as} over all time periods,

$$n_{amws} = \sum_{i=1}^{n_t} n_{as_i} \quad (4.8)$$

Another important measure for WHOlives.org is the number of jobs created because of the Village Drill. The number people employed per month operating drills (n_{pope}) is evaluated as

$$n_{pope} = n_{ds} * n_{popepd} \quad (4.9)$$

where n_{popepd} is the number of people employed per drill per month. The cumulative number of people-months of employment created operating drills is

$$n_{pme} = \sum_{i=1}^{n_t} n_{popei} \quad (4.10)$$

Time Series Evaluations

The productivity and impact measures presented in Equations 4.1–4.10 can be used to track productivity and impact over the past 5 years for the Village Drill. Time series plots are provided in Figures 4.4 and 4.5.

4.3.6 Manufacturing

The first Village Drill was manufactured in the US and shipped to Tanzania. For the next several years, drill frames were manufactured in Kenya and parts including the pulley and the drill bit were shipped from the US. In the latter portion of its 5-year history however, WHOlives.org moved the majority of the manufacturing back to the US and uses the shipping destination to determine the manufacturing location. If the drill will be delivered within 2000 km of the manufacturer in Kenya then it is made there and shipped via ground transportation. For any other location, the drill is manufactured in the US and shipped.

4.3.7 Delivery

The Village Drills are delivered in a crate that weighs 1100 kg (2425 lbs) and is 2.3 m (7.5 ft) by 0.9 m (3 ft) by 1.2 m (4 ft). When an organization purchases a drill, they also pay for a WHOlives.org worker to travel to their location and train them on the use of the drill. It only takes a few hours to learn how to put the drill together and operate it but the worker usually stays with

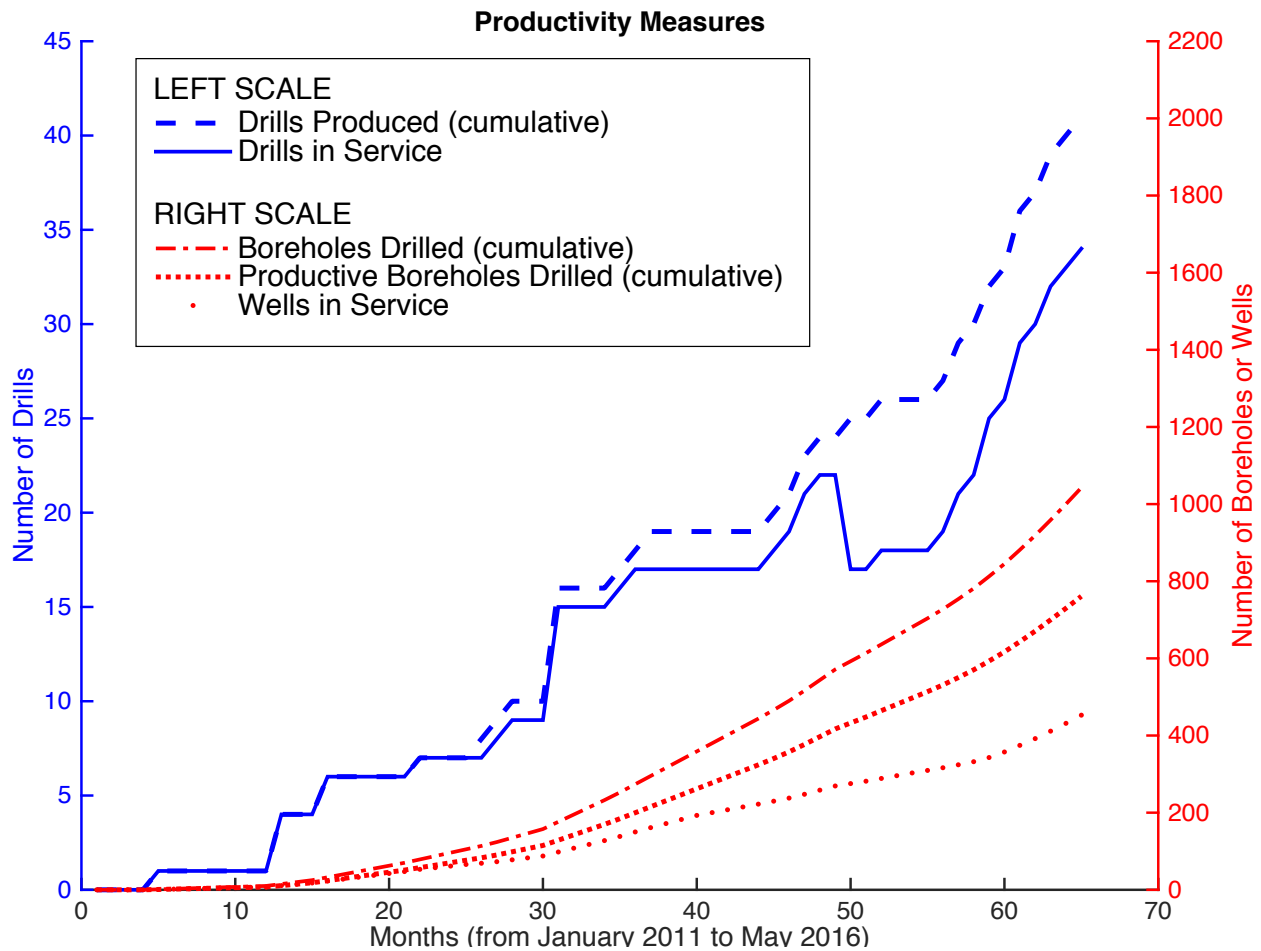


Figure 4.4: Time series plot showing productivity measures and wells in service.

the group for about 3 weeks and also trains them in drilling basics – how to find water, what to do when the drill gets stuck, casing a borehole, etc. Because drills have started going to countries farther and farther away from where these workers live, WHOlives.org has developed a training manual to send with the drill. This manual mostly consists of pictures that can be understood by speakers of any language.

4.3.8 Revenue Model

It is essential for people engaged in engineering for global development to understand how the hoped-for impacts will be paid for before and after the product is released to the market. Without such an understanding and a plan for funding the impact, it is unlikely that the effort

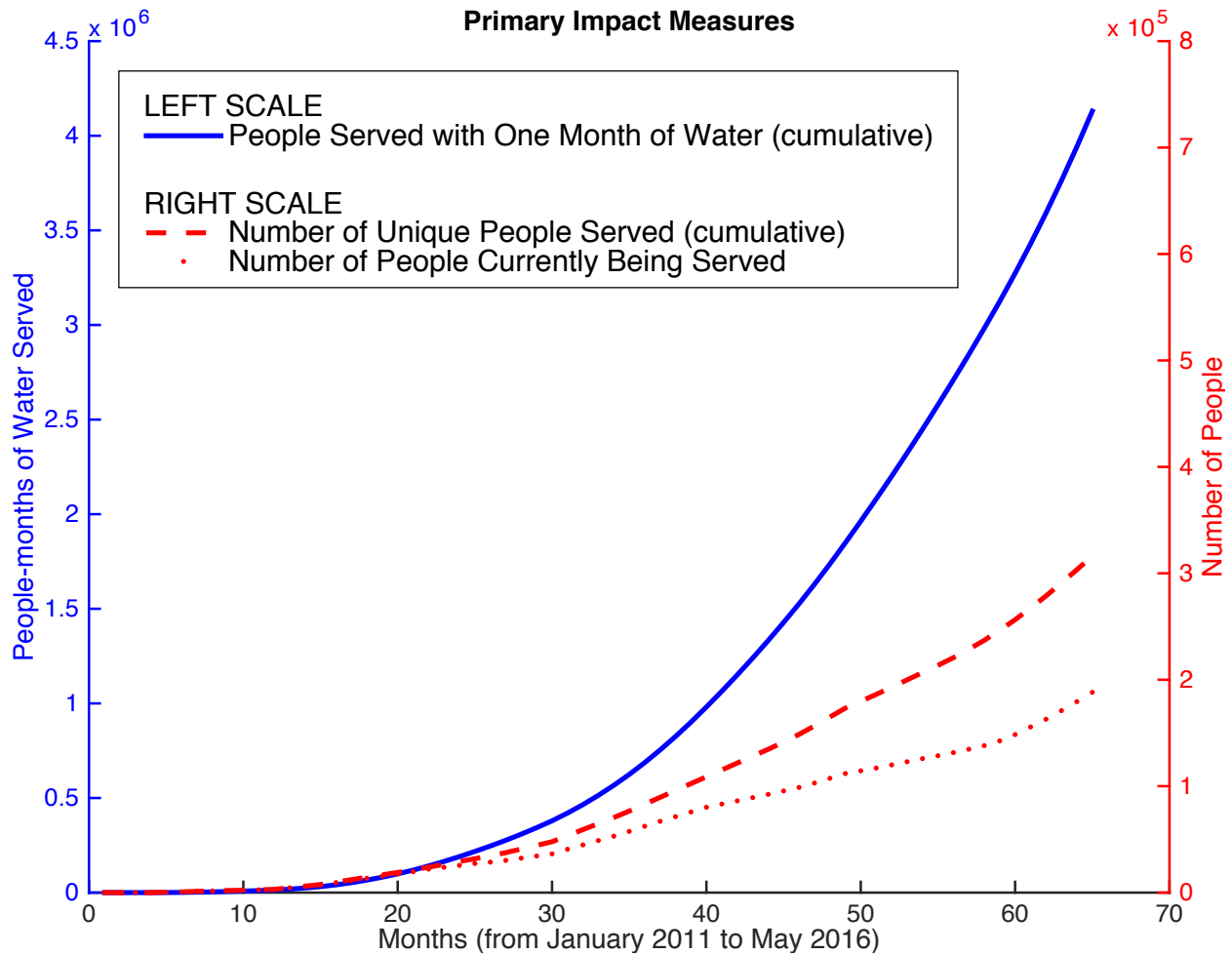


Figure 4.5: Time series plot showing the primary impact measures. The total number of people-months of water served is 4,129,945. The number of people who have access to a well (at time period 65 ($n_t = 65$)) with a functioning pump equals 188,176, while the number of people who could have access to water if all pumps were serviced equals 316,281.

will have a lasting effect [43]. With the intent to be financially sustainable, WHOlives.org chose to design, manufacture, and sell a well-drilling system that would generate income to run the organization. To track financial sustainability, WHOlives.org has used a simple cash flow analysis. The cashflow history is shown in Fig. 4.6. The model includes the following terms:

- n_{d_v} Number of drills invoiced for month
- n_{w_v} Number of drawings invoiced for month

I_t	Total income for month
I_{d_v}	Income: invoice of one drill
I_{w_v}	Income: invoice of one set of drawings
I_o	Income: donations
E_t	Total expenses for month
E_c	Expense: cost of goods sold
E_h	Expense: operating overhead
E_s	Expense: salaries
C_i	Cashflow for i -th time period

The cashflow for the i -th time period is

$$C_i = I_t - E_t \quad (4.11)$$

where the income and the expenses for each period are calculated as follows:

$$I_t = (I_{d_v} * n_{d_v}) + (I_{w_v} * n_{w_v}) + I_o \quad (4.12)$$

$$E_t = (E_c * n_{d_v}) + E_h + E_s \quad (4.13)$$

The values for E_c , E_h , and E_s vary for different times during the past five years, as shown in Table 4.3. This data comes directly from WHOlives.org's records.

WHOlives.org priced the drill so that it would cost less than creating one borehole using traditional drilling methods, making it a more attractive option to an NGO than paying for a single well. The price is also affected by the cost of producing the drill. In Tanzania, a traditional well costs between \$15,000 and \$20,000 USD so they started selling Village Drills for \$14,000 USD, then increased to \$16,000 USD and finally to \$18,000 USD. The increases in price are largely because of higher quality drill bits being included in the drilling system.

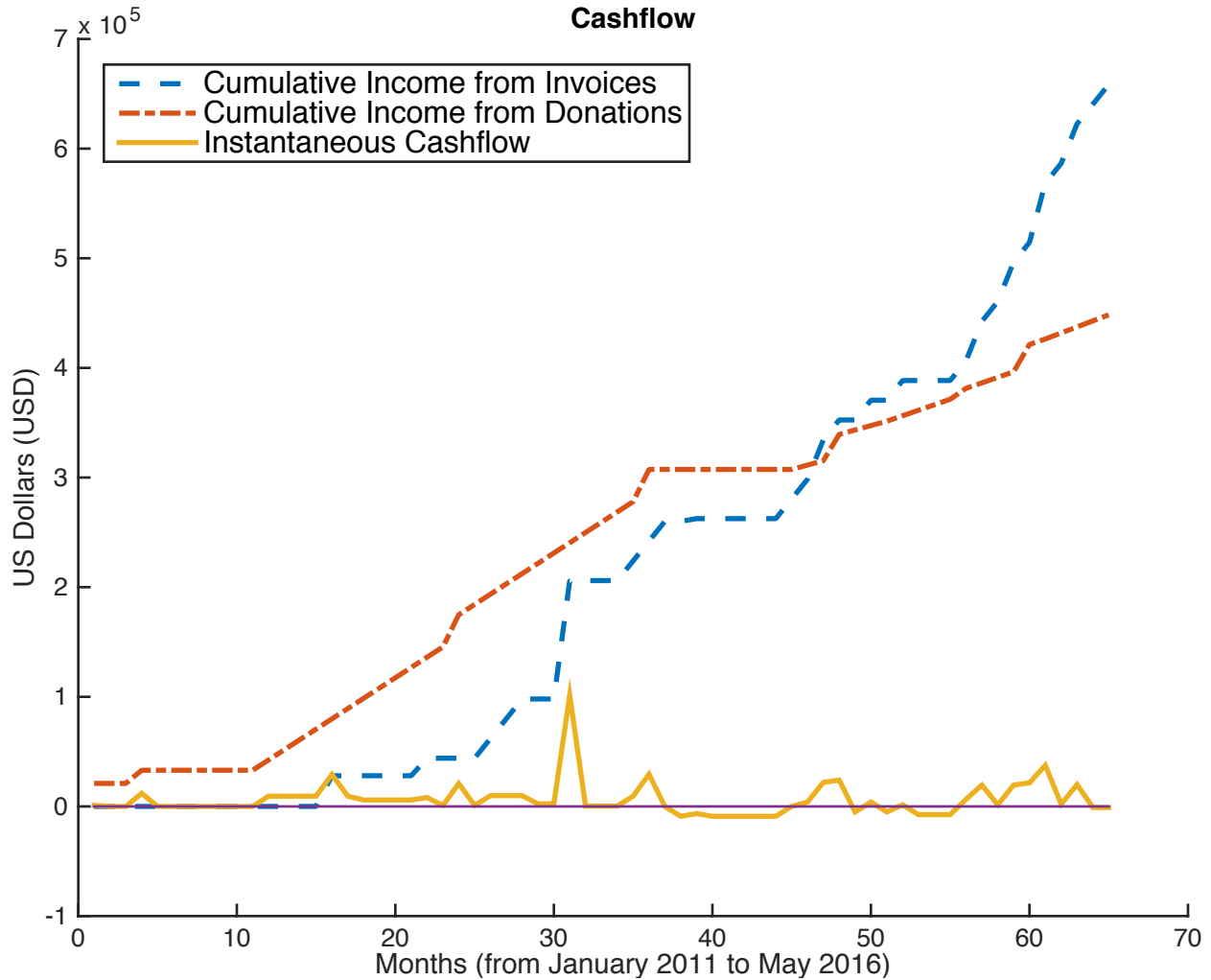


Figure 4.6: Time series plot showing incomes and cashflow. Zero income shown as baseline.

WHOlives.org has received a total of \$658,500 through drill invoices, and a total of \$448,375 to support development, start-up, and other operational costs.

4.3.9 Uncertainty Analysis

We recognize that modeling the impact of the Village Drill is not trivial. It requires WHOlives.org to estimate values for the models' input parameters. We also acknowledge that there will be uncertainty regarding the accuracy of this and any estimation. For this reason it is essential to the Village Drill case study that the uncertainty of the impact analysis be quantified and used to

Table 4.2: Uncertainty Analysis Results (Including all Time Periods)

Measure	Mean	Std Dev	97.6% conf.	99.9% conf.
n_{ws}	458	101.51	≥ 255	≥ 154
n_{pops}	190,510	43,838	$\geq 102,830$	$\geq 58,996$
$n_{popsmax}$	316,670	72,862	$\geq 170,940$	$\geq 98,082$
n_{pmws}	4,201,900	1,040,700	$\geq 2,120,400$	$\geq 1,079,600$
Input	Mean	Std Dev		
n_{bpm}	1.25	0.25		
n_{hub}	500	33		
n_{rim}	160	11		
Δn_{dos}	0	1		
f_{hub}	0.78	0.03		
f_a	0.06	0.0066		
l_{mbf}	10	1		
p_{fms}	0.4	0.033		

draw conclusions with higher levels of confidence than can be done with a deterministic analysis alone.

For the analysis carried out in this chapter, three types of estimations were used: Those made about the entire set of drills using data from only a sample; those made about all time periods using data from only a sample of periods; and those made to the best of our ability even though that ability is known to be imperfect.

Table 4.2 shows the estimated mean and standard deviation for the eight input parameters (lower portion of table) used to calculate the four primary impact measures (upper portion of table). The choice of mean values for each of the inputs were discussed in previous sections of this chapter. The term Δn_{dos} represents the difference between the number of drills believed to be out of service and those actually out of service. This term is added to Equation 4.1 when the uncertainty analysis is carried out. The standard deviations were chosen carefully, based largely on experiences gained from five years of manufacturing/sales/distribution/drilling and on straightforward reports from the WHOlives.org drilling teams. After the mean of each value was chosen, consideration was made as to how much larger and smaller it could actually be at the extremes. In each case, a Gaussian distribution was assumed and the amount larger was divided by three to calculate the standard deviation.

A Monte Carlo simulation, using 200,000 samples, was carried out to better understand how variations in input parameters translate to the primary impact measures. The result of the simulation is shown in Table 4.2 for each of the four primary impact measures, and in Figure 4.7 for the cumulative number of people-months of water provided.

The right side of Table 4.2 shows the final stage of the uncertainty analysis. Here the values for the primary impact measures are provided based on 97.6% and 99.9% confidence intervals. These numbers can be interpreted by considering the confidence lines shown in Figure 4.7. We are 97.6% confident that the actual value for *people-months of water provided* is in the region to the right of the line labeled 97.6%.

4.4 Discussion and Conclusion

This chapter has presented a case study on the Village Drill. The purpose of this case study was to present unobscured and unembellished facts and figures about the actual development and sustaining of a product engineered for a developing world market and setting. Our intention has been to present the drill and its data as a way of providing a more complete accounting of how impact is measured and the product is sustained after the bulk of the product development is complete. Additional information about the Village Drill can be found at www.villagedrill.com.

It's worth returning to the case study's question: *What impact has the Village Drill had on water-poor individuals?* Using a non-deterministic analysis, this study concludes with 97.6% confidence that over 170,000 people have been impacted (via access to drinking water) by the Village Drill, and that over 2 million people-months of water have been provided. The Village Drill has done this by producing over 1000 boreholes, 761 of which have led to water. While so doing the Village drill has employed 238 people for a total of 5,838 months of employment.

In the literature surrounding engineering for global development, case studies with years of data post market-introduction are rare. Nevertheless, when author's have access to the data and organizations are willing to share, such cases should be told and used to inspire and inform successful engineering for global development. They can be a basis for comparison and the venue for discussion and growth within the community. We welcome constructive discussion – in favor or against the efforts undertaken for the Village Drill.

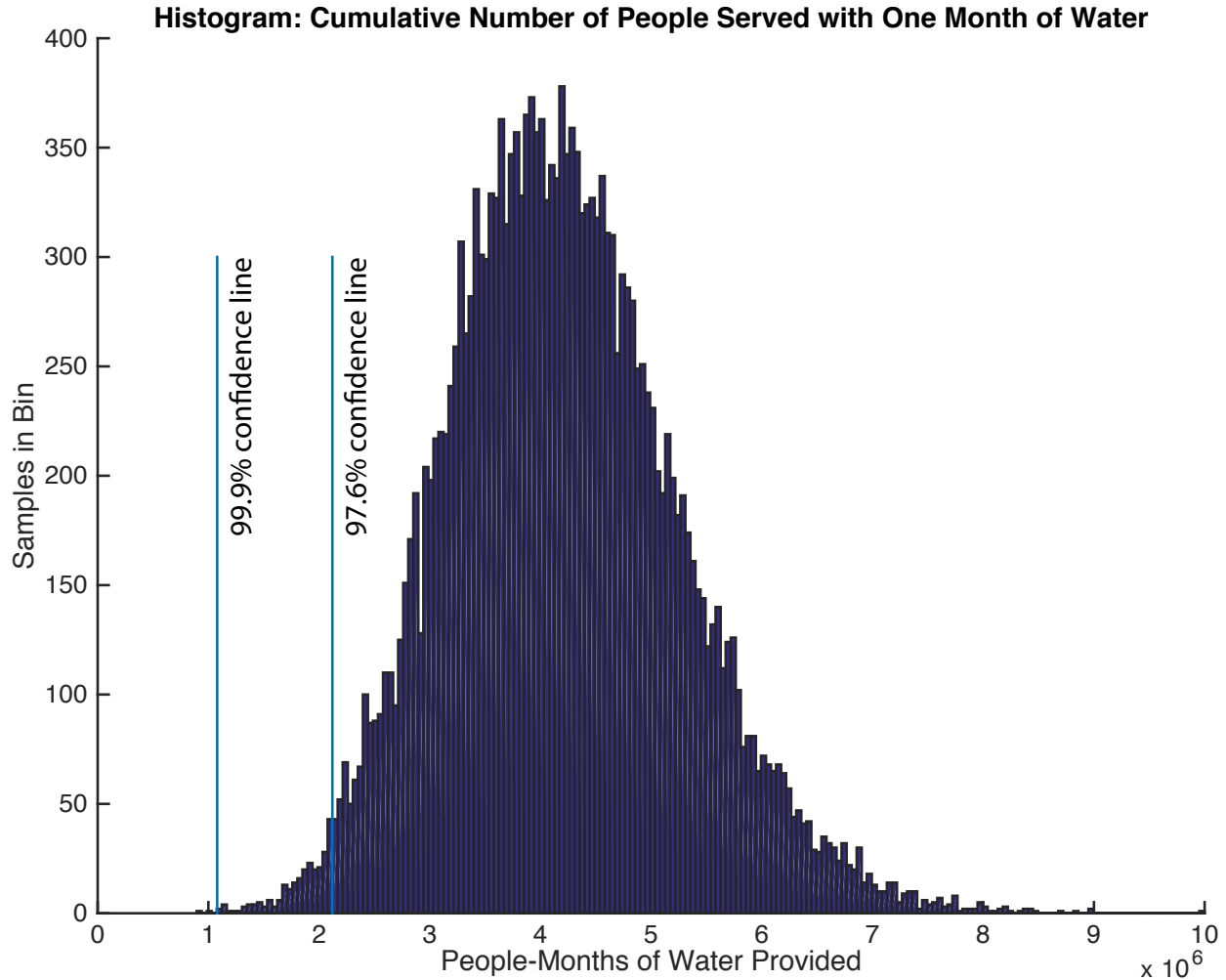


Figure 4.7: Histogram resulting from the uncertainty analysis carried out on the cumulative number of people-months of water provided (n_{pmws}). The mean and standard deviation for this data are shown in Table 4.2.

There are several important observations that can be made based on the data presented in this case study. Some of our observations include:

1. Accounting: There is a substantial benefit to reporting on the engineering for global development efforts *after* there is data to describe the actual challenges and impacts. This is markedly different than reporting on development efforts with only an initial field study as evidence of impact.
2. Evolution: Impact analysis can and should influence the ongoing evolution of the product. Impact analysis indicates whether a product and the system that supports it does what it's

supposed to do. For the Village Drill, the analysis has resulted in various considerations for improving the drill and the program that supports it. For example, the data gathered shows that the average number of boreholes created per month per drill is 1.25; and since it takes approximately three days to drill a borehole, improvements in product cost or transportability, and/or improvements in the workforce can be made that will result in reaching more drill sites throughout the month and therefore improve the Village Drill impact.

3. **Sustaining:** There is a significant amount of post-engineering support that needs to be given to a product engineered for a developing world setting and/or market. Figure 4.2 shows 17 field trips taken by WHOlives.org to strengthen the training, sales, manufacturing, distribution, and other aspects of the product. Including such information is a valuable part of case studies because too many engineers fail to consider the costs (financial, temporal, and human) of supporting the design after an initial field study.
4. **Timing:** For many of us, it is difficult to envision the timing of a project centered on engineering for global development. Though it is only one case, and timelines change case by case, the timeline shown in Figure 4.2 provides useful information not found in the engineering for global development literature. It shows, for example, that only a few weeks passed from the founder's first trip to Africa before they founded WHOlives.org. And that within a few months they connected with strategic partners to develop the drill. It shows that the bulk of the product development and engineering took place in less than 8 months. An interesting insight that can be gleaned from Figure 4.2 is that WHOlives.org was focused on being successful in Kenya and Tanzania before attempting to expand out to 13 other countries.
5. **Unidealized:** Without the knowledge gained from struggling to sustain a product designed for the developing world, it is easy to idealize the conditions of its impact. This case study illustrates this in a valuable way. Any initial estimates of product impact would likely not consider realistic conditions such as wells with pumps that fail to get serviced and subsequently fail to provide water. As another example, it would have been easy to assume the traditional value of every well serving 1000 people, without five years of experience that show the numbers to be smaller where the Village Drill is being used (500 people for a well in a village center, and 160 people for a well placed in the outskirts of a village) .

6. Uncertainty: There is uncertainty in the data related to products engineered for the developing world. This uncertainty must be accounted for so as to put into perspective the conclusions drawn. The uncertainty analysis presented as part of this case study shows a large amount of uncertainty. Without doing such an analysis one would expect the uncertainty to be smaller and therefore (erroneously) place more value on the deterministic study presented earlier in the chapter. Though the uncertainty is large, it is quantified. Such analysis allows the authors to state with a certain degree of confidence that Village Drill impact is quantifiably positive.
7. Assessment: The data presented in this chapter can be used to perform other assessments that may be useful to promote the cause of engineering for global development. For example, the product development team for the Village Drill spent approximately 2000 man-hours conceptualizing, engineering and testing the Village Drill. That effort has had a quantifiable social impact; using the data provided in Table 4.2 for 97.6% confidence, we can say that for every engineering hour spent, 1,060 people-months of water have been delivered. Or using the data presented in Table 4.1 we can say that a month of drinking water was delivered for \$0.27 USD per person. Such information can play an important role in fundraising and motivation.

We believe that these kinds of observations are generally missing from the literature surrounding engineering for global development. We also believe that when case studies such as the one presented in this chapter are shared in the archival literature it provides an important basis for comparison and a valuable venue for discussion. This is particularly needed in a field of growing interest such as *engineering for global development* and *design for the developing world*.

4.5 Raw Data Used for Case Study

The raw data used in this case study is provided in Table 4.3. This data is included so that the impacts and plots can be recreated and so that others can use the Village Drill case study as a basis for further research. We note that COGS are the cost of goods sold, meaning how much it costs WHOlives.org to manufacture the drill. The column labeled Overhead provides the general

operating expenses not including salary expenses. The column labeled Salary provides salary expenses.

Table 4.3: Raw data used in the Village Drill case study.

Time Period (month)	Drills Added to Fleet (number)	Known Idle Drills (number)	Drill Price (USD)	COGS (USD)	Drawings Sold (number)	Drawing Price (USD)	Donations (USD)	Overhead (USD)	Salary (USD)
1	0	0	0	0	0	0	21000	20000	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	12000	0	0
5	1	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	9375	0	0
13	3	0	0	0	0	0	9375	0	0
14	0	0	0	0	0	0	9375	0	0
15	0	0	0	0	0	0	9375	0	0
16	2	0	14000	8200	0	0	9375	0	0
17	0	0	0	0	0	0	9375	0	0
18	0	0	0	0	0	0	9375	3500	0
19	0	0	0	0	0	0	9375	3500	0
20	0	0	0	0	0	0	9375	3500	0
21	0	0	0	0	0	0	9375	3500	0
22	1	0	16000	8700	0	0	9375	3500	5000
23	0	0	0	0	0	0	9375	3500	5000
24	0	0	0	0	0	0	29375	3500	5000
25	0	0	0	0	0	0	9375	3500	5000
26	1	1	18000	9000	0	0	9375	3500	5000
27	1	1	18000	9000	0	0	9375	3500	5000
28	1	1	18000	9000	0	0	9375	3500	5000
29	0	1	0	0	0	0	9375	3500	3500
30	0	1	0	0	0	0	9375	3500	3500
31	6	1	18000	9000	0	0	9375	3500	3500
32	0	1	0	0	0	0	9375	3500	5500
33	0	1	0	0	0	0	9375	3500	5500
34	0	1	0	0	0	0	9375	3500	5500
35	1	1	18000	9000	0	0	9375	3500	5500
36	1	1	18000	9000	0	0	29375	3500	5500
37	1	2	18000	9000	0	0	0	3500	5500
38	0	2	0	0	0	0	0	3500	5500
39	0	2	0	0	1	2500	0	3500	5500
40	0	2	0	0	0	0	0	3500	5500
41	0	2	0	0	0	0	0	3500	5500
42	0	2	0	0	0	0	0	3500	5500
43	0	2	0	0	0	0	0	3500	5500
44	0	2	0	0	0	0	0	3500	5500
45	1	2	18000	9000	0	0	0	3500	5500
46	1	2	18000	9000	0	0	4000	3500	5500
47	2	2	18000	9000	0	0	4000	3500	5500
48	1	2	18000	9000	0	0	24000	3500	5500
49	0	2	0	0	0	0	4000	3500	5500
50	1	8	18000	9000	0	0	4000	3500	5500

Table 4.4: Raw data used in the Village Drill case study continued.

Time Period (month)	Drills Added to Fleet (number)	Known Idle Drills (number)	Drill Price (USD)	COGS (USD)	Drawings Sold (number)	Drawing Price (USD)	Donations (USD)	Overhead (USD)	Salary (USD)
51	0	8	0	0	0	0	4000	3500	5500
52	1	8	18000	9000	0	0	5000	3500	9000
53	0	8	0	0	0	0	5000	3500	9000
54	0	8	0	0	0	0	5000	3500	9000
55	0	8	0	0	0	0	5000	3500	9000
56	1	8	18000	9000	0	0	10000	3500	9000
57	2	8	18000	9000	0	0	5000	3500	9000
58	1	8	18000	9000	0	0	5000	3500	9000
59	2	7	18000	9000	0	0	5000	3500	9000
60	1	7	18000	9000	0	0	25000	3500	9000
61	3	7	18000	9000	0	0	5000	3500	9000
62	1	7	18000	9000	0	0	5500	3500	9000
63	2	7	18000	9000	0	0	5500	3500	9000
64	1	7	18000	9000	0	0	5500	3500	12000
65	1	7	18000	9000	0	0	5500	3500	12000

CHAPTER 5. AN EXPERIMENT IN CROSS-BORDER DESIGN ETHNOGRAPHY IN THE DEVELOPING WORLD

Ethnography, a tool traditionally used by social scientists, has been adopted by product design engineers as a tool to build empathy, understand customers and their contexts, and learn about needs for a product. This tool is particularly valuable for designers from the developed world working on products for customers in developing communities as differences in culture, language, and life experience make the designer's intuition less reliable in these communities. This chapter reports the use of design ethnography under a variety of cross-border conditions in the developing world. The data analyzed here come from field studies completed in four different countries on four different continents. Researchers had varying degrees of cultural familiarity, language fluency, and community partner participation in each location. Other factors were also included in the study such as the effects of gender and age of the respondents, the ethnographic activity used, and others. Some of the results are intuitive and some are surprising, but all are quantified through rigorous statistical analysis. The results of this study can help design teams plan their own ethnographic activities to increase the likelihood of collecting information that is useful for making product design decisions based on the conditions of their particular project.

5.1 Introduction

The word *ethnography* has different meaning in different disciplines [52]. Traditional ethnography in the social sciences is the study of other cultures, contexts, and people in their natural settings [53] as they go about their everyday lives [54]. It is the process of learning about and recording the culture of a particular group through immersion and participation in the context of that group [302]. In the social sciences, ethnography can also refer to a written record of cultural practices [302]. Nevertheless, a fundamental purpose of ethnography is to help the ethnographer

understand context and culture, whether that culture is as narrow as a profession (e.g. surgeon) or as broad as a geographic region (e.g. Southeast Asia).

The principles of ethnography have been used by product design engineers to build empathy, understand customers and their contexts [55], and learn about needs for a product [56]. When used in this way, these activities are referred to in the literature as *design ethnography*. Design ethnography is focused on collecting information about problem-specific context and needs [55] whereas traditional ethnography is focused on the broader purpose of understanding culture and context in a holistic way [57]. Design ethnography is often completed more quickly (hours or weeks) than traditional ethnography (weeks or years). Some researchers and practitioners have developed frameworks for completing design ethnographies [58]–[62], but very few have quantified any aspect of the process.

In this chapter, we focus on quantifying aspects of ethnography for a specific subset of design ethnography called *cross-border design ethnography*. Cross-border design ethnography is design ethnography completed across national borders where differences in language and culture can strongly influence the usefulness of the design ethnography. The aspects quantified in this study include the influences of cultural familiarity, language fluency, ethnographic activity used, information source type, gender and age of the respondent, use of prototypes during ethnographic activities, and the type of need statements collected on the ability of the design team to collect information that is useful in making product design decisions.

The results of this chapter are particularly useful when designers from developed communities are designing products for customers in developing communities. Designers from the developed world have vastly different life experiences than those living in poverty and are typically unfamiliar with the language, culture, and context of the place where the product they are designing will be used. As a result, their intuition is less reliable for making design decisions about products used in these communities [63], [64]. For example, as this study began, we used our extensive experience in developing communities and knowledge of the literate to determine three problem areas to focus our ethnographic studies on. As researchers arrived in the field, it quickly became clear that none of the three problem areas we had previously identified were of interest to the members of any of the four communities visited. In each location, there were other, more pressing needs that we had not anticipated. This shows the importance of field studies in deter-

mining actual customer needs; customer needs are difficult to determine without experience in the context and interaction with potential customers and it is difficult for the designer to avoid making assumptions to fill in gaps in the understanding of customer needs. When these assumptions are the basis for product design decisions, it generally leads to poorer decisions and to products that are less desirable to the intended customers.

Conducting cross-border design ethnography through immersion in the context where the product will be used can help designers challenge assumptions and better understand the needs of customers. When customer needs are more accurately understood, the design team is better able to develop a product that meets those needs and has the desired impact, be it to alleviate poverty or to enter or succeed in a foreign market.

Despite the benefits offered by cross-border design ethnography, very little appears on this topic in the archival literature. While we believe that some engineering practitioners are using ethnographic principles, we found only one case where design ethnography across borders was explicitly used and reported on. Sarvestani and Sienko [56], [303]–[305] used cross-border design ethnography in Uganda to inform the design of a medical device that improves the safety of a long-standing traditional ceremony while maintaining its cultural significance. In this case, the use of ethnography allowed them to collect tacit information from a variety of stakeholders – information that “would have been impossible to obtain in a conventional laboratory setting.” This information allowed the team to make design decisions that led to a culturally acceptable product. Sarvestani and Sienko “formed a multidisciplinary team that included engineers, clinicians, sociologists, and public health and business experts” to conduct their cross-border design ethnography.

The work presented in this chapter is distinct from the work of Sarvestani and Sienko in two key ways: first, the present chapter quantifies the influence of various factors on the usefulness of the ethnographic study, and second, the ethnography in the present chapter was completed exclusively by design teams that did not include social scientists trained in ethnography. The latter was chosen based on the assumption that, while multidisciplinary teams may be ideal for this work, design engineers in industrial and academic settings are often required to conduct these studies without the assistance of social scientists.

In the following section, the experiment is described including more detailed information about each of the conditions and locations. Next, the post field-study analysis is described includ-

ing the statistical analysis of the data collected. Key results are then outlined along with some discussion of the impact of these results for design teams conducting ethnographic studies in developing communities. Lastly, some concluding remarks are made about how these results can help design teams plan their own ethnographic activities to increase the likelihood of collecting information that is useful for the conditions of their specific project.

5.2 The Experiment

In this section, the conditions of the field studies are described, as are the locations of the field studies. The ethnographic activities are then outlined along with a description of how the information was collected and recorded. Lastly, a description of the timing of each field study is included. In each of the locations, researchers working in pairs or groups of three completed the field studies. The majority of the field work was completed by four individuals, with two additional individuals assisting with one field study.

5.2.1 Description of the Conditions

The central question this experiment was designed to answer was how the conditions of cultural familiarity, language fluency, and community partners affect the designer's ability to collect information that is useful for making product design decisions. The locations of the field studies were chosen to accommodate these conditions and the conditions are described in this section.

Many other factors were also tested throughout this experiment. Some factors did not yield meaningful results but those that did are reported on in this chapter. The factors that yielded meaningful results include the effect of the ethnographic activity used, information source type, gender and age of the respondents, use of prototypes, and type of need statements. These factors are described in the following section.

While there is much debate about the overlap between language and culture [306], we chose to separate these two factors for this study to more clearly identify the affect of each. In this study, there were 3 conditions:

1. Cultural familiarity, language fluency, and community partners
2. Language fluency and community partners

3. Community partners only

The first condition describes a situation in which the researchers are familiar with the culture, fluent in the local language, and have community partners to facilitate ethnographic activities. In this study, a researcher is described as familiar with the culture if they had been immersed in the culture for an extended period of time. While it is unclear exactly what the threshold should be, both researchers who are described as familiar with the culture in this study were previously immersed in the culture – including the specific location chosen for the experiment – for 22 consecutive months. Those researchers described as unfamiliar had typically not spent any time immersed in the culture. In one case, one of the three researchers had spent up to 8 weeks in the location before the experiment began but the design team was still described as culturally unfamiliar.

The second condition describes a situation in which the researchers are fluent in the local language and have community partners to facilitate ethnographic activities. In this study, a researcher is described as fluent if they are able to express themselves easily and accurately in the local language *and* easily and accurately understand the spoken and written language.

The third and final condition describes a situation in which the language and culture are unknown to the researchers. In this study, the researchers relied heavily on their community partners and on a translator to perform ethnographic activities in this condition.

A condition without community partners was not included in this study. Our past experiences and what is found in the literature for ethnographic studies indicate that community partners are key because they help researchers build trust with members of the community and that relationship of trust is essential for collecting information. Because significant resources were required to perform an ethnographic study in each location, we chose not to use our limited resources performing a study in a location with no community partners. We did notice that in locations where we had stronger community partners, the researchers were able to conduct ethnographic activities more easily and collect more information.

5.2.2 Description of the Locations

This experiment in cross-border design ethnography is uncommon because ethnographic activities were conducted in four different countries on four different continents. The first portion

of the study was completed in Itacoatiara, Brazil, a town of 95,700 people along the Amazon River in Northern Brazil. The two researchers who traveled there are both American males who are familiar with the culture, fluent in the local language (Portuguese), and had community partners willing to assist with ethnographic activities, as described by condition 1.

The second portion of the study was conducted in a small community on the eastern edge of Madrid, Spain called Cañada Real Galiana. While Spain is not a developing country, this area was chosen for the study because this section of Madrid is a developing community in many ways. The area is public land and several decades ago, people began building homes there on land they didn't officially own. Some residents of this community now have access to basic utilities but there are still unpaved roads, homes made from corrugated metal, and a lack of many of the services that distinguish a community as developed. Members of this community live under the constant threat of being displaced from their homes and have a significantly lower quality of life than their neighbors in the city of Madrid.

The two researchers who traveled to Cañada Real Galiana are American, one female and one male who is fluent in the local language (Spanish). Both were unfamiliar with the culture and they had community partners to help with ethnographic activities. This location is described by condition 2. The researcher here who speaks Spanish is fluent in Peruvian Spanish, which is distinctly different from the Spanish spoken in Spain. Because of this, the words being said were understood but the slang used and the cultural significance of those words was sometimes lost. This allows us to draw some conclusions about the affect of cultural familiarity – or lack thereof – on the researchers' ability to conduct an ethnographic study while still being able to directly communicate with individuals in the community in their own language.

The third portion of this study was conducted mainly in Kigali, Rwanda, a city with a population of 1.1 million people. Excursions were taken to several other cities during the field study. The research team for this field study consisted of 3 Americans, two female and one male. All are fluent in English, which is one of three official languages in Rwanda, and one researcher is also fluent in French, another official language. The third official language is Kinyarwanda and none of the researchers is fluent in this language. Most ethnographic activities were conducted in English and the remainder were conducted in multiple languages with translation from Kinyarwanda or French to English as necessary. While one researcher had spent 2 months in Rwanda previously,

the 2 other researchers had no experience with the culture and the research team was considered unfamiliar with the local culture. Overall, this research team was fluent in the language, unfamiliar with the culture, and had community partners willing to help with ethnographic activities, as described by condition 2.

The fourth portion and final of the study was conducted in Visakhapatnam, a city of 2 million people on the southeastern coast of India. The researchers focused their ethnographic study on a small, lower-income fishing community called Vanivasipalam. The two researchers who traveled here are American, one female and one male. They were able to conduct some interviews in English, but the majority were conducted through a translator because they were unfamiliar with the local language (Telugu). In this location, the researchers were not fluent in the local language, were unfamiliar with the culture, and had community partners, as described by condition 3.

5.2.3 Description of Ethnographic Activities

Before any field studies began, we consulted with a sociologist who has decades of experience conducting ethnographic research and selected four ethnographic activities to use in each location [54], [57], [61], [62], [72], [116], [302], [307]. The four activities chosen were:

1. Interview - conduct personal and group interviews
2. Observations - spend time simply observing life in the community
3. Participation - participate in activities with community members
4. Community Maps - have community members draw maps to show where resources are located, where they spend their time, etc. to understand the layout and resources of the community

In each country, these activities were adapted slightly to be culturally appropriate.

The researchers found that their participation in activities always turned into interviews because they would ask questions as they were participating to gain deeper understanding. And often, ethnographic activities that started as interviews would include some kind of participation. Because of this overlap, it was difficult to clearly separate the two activities and they were combined into a single group called *interviews* for the analysis.

The community maps activity did yield some useful information but overall, the communities where field studies were conducted do not place the same significance on knowing the precise location of things that Western cultures often do. In communities where locations are often described as a set of directions in relation to key landmarks as opposed to a specific address, the concept of maps was not very culturally relevant. Because of this, so few pieces of information were collected from the community maps activity that it was excluded from the final analysis because none of the results were statistically significant.

As each of the activities were being conducted, the researchers would take quick notes, pictures, and sometimes video to record the events. At the end of each day, the researchers would write a detailed description of the activities of that day [54] in a field report. Information collected in field reports is compared to the information collected through each of the ethnographic activities in this analysis. The ethnographic activities listed previously were recorded separately from field reports. Field reports do not contain quotes from respondents or observations made while conducting a formal observation. Instead, they include the researchers' reflection on the activities conducted, their analysis of the information collected, and list of questions to be pursued next.

Respondents were selected for ethnographic activities based on their availability and their relationship to the community partners. In Brazil and India, the researchers spent time walking through neighborhoods or along rows of stores talking with people who were willing to talk. Other ethnographic activities were completed with individuals identified by community partners. In Spain and Rwanda, the researchers relied heavily on partners in the community to arrange respondents for ethnographic activities. In all locations, the researchers tried to balance the number of respondents based on gender, age group, and other characteristics.

Overall, 264 ethnographic activities were documented over the course of this study, resulting in 6050 piece of data that were used in the analysis.

5.2.4 Description of the Timeline

A different amount of time was spent in each location. In Brazil, the researchers had three separate trips over the span of one year. The first was two weeks in length and the purpose was to conduct an open-ended cross-border design ethnography to determine potential product opportunities. The information collected during this trip was given to a graduate product design

class and prototypes for four different products were developed. In the middle of the class, about 5 months after the first trip, a second one week trip was taken to conduct ethnographies specific to each of the four products. The information gathered on this trip was used to further develop one of the four products. After another four months of product development, a third trip of one week was taken to continue testing the product with potential users and develop manufacturing partners in the community.

The researchers were in Spain for two weeks doing an open-ended cross-border design ethnography and no prototypes were developed.

The researchers were in Rwanda for two weeks and focused on a specific problem area, which was a unique situation in this study as the others began as open-ended studies. This problem area specific approach was chosen because of the validation received from community partners regarding this problem area. The team brought a prototype for use during the field study and additional sketches and other low-fidelity prototypes were also used.

The researchers were in India for 7 continuous weeks. The first 3 weeks were spent doing an open-ended cross-border design ethnography and the final 4 weeks were spent focusing on a specific problem area identified during the first half of the field study. Several prototypes were made in the final weeks of the ethnographic study.

5.3 Analysis

This section describes the process used to organize the data after the ethnographic field studies were completed. Next, the statistical models used in the analysis are discussed, including the necessary equations. We then describe how we can determine the accuracy and appropriateness of the models and how the predictors included in the models were selected, followed by the definition of several statistical terms that will be used as the results are reported.

5.3.1 Post Field-Study Data Processing

Social scientists typically use a process called *coding* to organize data collected through ethnographic activities [308]–[310]. This coding allows a researcher to draw quantitative conclusions from qualitative data. Coding software allows researchers to develop *descriptors* and *codes*

to tag, organize, and compare the data. The software used for this analysis is called Dedoose. While this categorization is intrinsically subjective, a set of descriptors and codes was defined and outlined for this study. All of information was coded by one of two researchers for consistency and the researcher who collected the information in the field was the one who coded that information. The descriptor and code definitions are given in this section.

To begin the coding process, a written record of each of the ethnographic activities was uploaded to the coding software. Descriptors were then added to each record; they are tags that apply to the entire ethnographic activity. The descriptors used in this study were:

1. Researcher - identifies the team of researchers who conducted the activity
2. Country - identifies where the activity was conducted
3. Condition - identifies which of the 3 conditions were present (cultural familiarity, language fluency, and community partners)
4. Activity - identifies the activity as a field report or as one of the three activities used to collect information (interview, observation, or community maps)
5. Gender - identifies the respondent as female, male, a mixed group, or not applicable– as in observations
6. Age - identifies the respondent as a child (0-16 years), young adult (17-27), middle aged adult (28-49), senior (50+), or not applicable– as in a group interview or observations

The next level of analysis was to tag sections within each record with the appropriate codes. These sections are referred to as *excerpts* and can range from a few words to a few paragraphs, whichever is necessary to capture the idea that is being coded. Almost all excerpts had more than one code applied to them and some had up to 6 codes.

Typically, the coding process is iterative. First, a set of descriptors and codes was developed based on what we thought would yield the most meaningful results and these codes were applied to the data. As the analysis progressed, we identified additional patterns that would lead to meaningful results that were not part of the original set of codes or recognized that some code definitions needed refining so an updated set of codes was developed and the data were recoded. Some codes

do not provide any useful results; this is to be expected. These codes were not removed from the description of the final set of codes provided below.

1. Usefulness

- (a) High Usefulness - an excerpt that directly influences design decisions (e.g. “this prototype would be better if it were 6 inches wider”)
- (b) Medium Usefulness - an excerpt describing a problem to be solved by a potential product (e.g. “everything is wet during the rainy season”) or an excerpt that could potentially influence design decisions or provides a benchmark (e.g. “the most popular mobile phone sells for 8 USD”)
- (c) Low Usefulness - an excerpt that may be useful for understanding the customer or context but that would not directly influence a design decision (e.g. “my older sister studied civil engineering”) or an excerpt that is a researcher’s note made about the ethnographic process (e.g. “we have completed 40 interviews so far”)

2. Source

- (a) Primary Source - an excerpt describing a respondent’s own experience (e.g. someone describing what they do for a living)
- (b) Secondary Source - an excerpt from a respondent describing another person’s experience (e.g. describing their neighbor who is unemployed) or excerpts collected through a translator. We chose to code translated information as secondary source because this information was filtered by the translator. Some of what the respondent said was lost and some personal commentary from the translator was added, meaning the translator were describing another person’s experience to the researchers
- (c) Researcher’s Notes - an excerpt describing a researcher’s experience or their analysis of that experience

3. Interaction Setting

- (a) Primary Setting - excerpts when researchers were in the place a respondent was describing (e.g. their home or farm) or when the information was a researcher's note made while in the setting the information is describing
- (b) Secondary Setting - excerpts when researchers were with a respondent but not in the place being discussed (e.g. in their home talking about their workshop down the street)
- (c) Not Applicable - excerpts where the information is independent of any location (e.g. the fact that a person is married)

4. Context

- (a) Individual - an excerpt that describes someones individual context (e.g. number of siblings)
- (b) Societal - an excerpt that describes an aspect of the context shared by many members of the community (e.g. government programs in the community)

5. Needs

- (a) Explicit - an excerpt stating a specific need (e.g. "we need a factory to create more jobs")
- (b) Implicit - an excerpt that was not stated as specific need but that describes a problem that could be solved (e.g. "there is high unemployment in this community")

6. Prototypes - an excerpt collected while respondents were interacting with prototypes or other hardware (e.g "it should have walls on all 4 sides")

7. Counting Observations - an excerpt that is an observation where something was counted by the researchers (e.g. "the bag of fish was 2 feet by 3 feet by 1.5 feet"). This code was added to determine if attempts to quantify observations led to more useful information

8. Income - an excerpt containing information about income (e.g. "I make about 40 Brazilian Reais a day, its enough to pay my bills")

9. Comments on Methods - any researcher’s notes made about the ethnographic process as the field study progressed (e.g. “we need to speak to more women to balance our respondents’ gender”)

The coding process resulted in the following data:

Table 5.1: Summary of Coded Data Counts.

Country	Number of Ethnographic Activities	Number of Excerpts	Number of Code Applications
Brazil	158	2092	9638
India	52	1462	4904
Rwanda	41	1715	5587
Spain	13	781	2606
Total	264	6,050	22,735

5.3.2 Statistical Analysis

The software used to code the data provides analysis functions that are useful for observing general patterns, ratios, and counts, but does not have the capacity for rigorous statistical analysis. For this, the coded information was uploaded into other software that was used to analyze and interpret the relationships between the factors coded for. The software used in this analysis is called Stata. After iterating through several statistical analyses, it was determined that the most accurate and useful results came from the combination of two multiple logistic regression models. A multiple logistic regression model is one that has a binary dependent or outcome variable and multiple independent or predictor variables. Two separate models were needed to analyze this data set because the outcome variable for this study, usefulness, has three categories: low, medium, and high. This refers to the usefulness of that excerpt in making product design decisions.

We experimented with other statistical models that accommodate an outcome variable with three categories, specifically the proportional odds model. This model was inappropriate for the data set because the data set did not meet the parallel lines assumption required for the use of this model.

One of the multiple logistic regression models chosen for this study is a comparison of excerpts coded Low Usefulness to the combined group of excerpts coded Medium Usefulness and High Usefulness. This model will be referred to as the L-MH Model (or Low to Medium and High Model) in this chapter and includes all of the 6050 excerpts in the data set.

The other multiple logistic regression model chosen for this study omits the Low Usefulness excerpts and compares the excerpts coded Medium Usefulness to those coded High Usefulness. This model will be referred to as the M-H Model (or Medium to High Model). Because the Low Usefulness excerpts are omitted, the M-H Model includes just 2564 excerpts. It should be noted that this model does not include any excerpts collected in Spain because there were no excerpts from Spain coded High Usefulness. It also doesn't include any excerpts collected from children for the same reason.

A simple logistic regression consists of a binary outcome variable and just one predictor variable. The equation for this regression is:

$$\ln \left[\frac{p}{1-p} \right] = \beta_0 + \beta_1 X \quad (5.1)$$

where p is the probability of success, which is defined as either medium or high usefulness in the L-MH Model or as high usefulness in the M-H Model, β_0 is a constant that describes the intercept, and β_1 is the coefficient associated with variable X , which represents a predictor.

A multiple logistic regression consists of a binary outcome variable and multiple predictors. The equation can be expanded to include i variables as shown:

$$\ln \left[\frac{p}{1-p} \right] = \beta_0 + \beta_1 X_1 + \beta_2 X_2 \dots \beta_i X_i \quad (5.2)$$

where β_i is the coefficient for the i th predictor, X_i .

This regression gives a constant, β_0 , for the model and a coefficient β_i for each predictor. These coefficients are used to determine the effect each variable has on the researchers' ability to collect information, as described below.

5.3.3 Determining the Accuracy of the L-MH and M-H Models

A model consists of both the statistical analysis chosen (in this case, multiple logistic regression) and the variables included in the analysis. When an additional variable is included in the model, it is said to be controlled for. When a variable is controlled for, it is given its own term in Equation 5.2 and assigned its own coefficient, thus isolating it from the other terms. This removes the effects of the other variables from the coefficient reported, allowing us to report the effect of each predictor independently.

Selecting which predictors to include in a model can be a subjective process that has a significant impact because the predictors included or excluded have an effect on the coefficients reported for the other predictors. There are two key measures that indicate the accuracy of the model and these were used to determine as objectively as possible which combination of predictors was best for this data set.

The first measure of the accuracy of a model is chi squared (χ^2) statistic. Similar to a p-value for an individual variable (described below), if the χ^2 statistic is below a certain threshold, the model is said to be statistically significant. As per the standard in the social sciences, the models in this study are said to be statistically significant if $\chi^2 \leq 0.05$. All of the models described in this analysis have $\chi^2 < 0.0001$ and meet this requirement.

The second measure is called the log likelihood, which is a measure of how well the model fits the data. It is not an absolute measure, but can be used to compare two models. If a variable is added to the model and the log likelihood moves closer to 0, the model is said to be a better fit than before the additional variable was included.

To use the log likelihood, we first evaluated an initial model including just one predictor and recorded the log likelihood value of that model. Subsequent predictors were added one at a time and the log likelihood value of each intermediate model was compared to the previous one. If we found that including a specific predictor improved the log likelihood at least 10 points in each of the two models, the predictor was included in the final models. Otherwise, the variable was omitted from the models. The predictors that were included in the final models are Ethnographic Activity, Conditions, Gender, Prototypes, Age, Source, Needs, Context, and Income.

5.3.4 The Odds Ratio

As described above, each predictor has an associated coefficient, β_i . There is a unique coefficient for each predictor included in the model. When the exponent of the coefficient is taken, the value is known as the odds ratio.

$$OR = e^{\beta_i} \quad (5.3)$$

Like the log likelihood value, odds ratios are not an absolute measure but can compare one predictor to another. Equation 5.4 gives further meaning to the odds ratio.

$$OR = \frac{p(1)/(1-p(1))}{p(0)/(1-p(0))} \quad (5.4)$$

The numerator is the probability of a successful outcome over the probability of failure when the predictor is equal to 1. The denominator is the probability of a successful outcome over the probability of failure when the predictor is equal to 0. This gives the likelihood of success with one predictor over another.

There are two ways to report an odds ratio. First, an odds ratio can be reported for a predictor as a whole. This is useful when the predictors are continuous or ordered variables, such as temperature. For example, if the odds ratio for temperature was 1.67, it means that a successful outcome is 1.67 times more likely as the temperature increases. In our data set, the predictors are categorical variables, meaning there are discrete values but these values are not necessarily ordered. For example, the predictors gender has four discrete values: (i) not applicable (as in observations), (ii) female, (iii) male, or (iv) a mixed gender group. These values cannot be meaningfully ordered so one odds ratio for the entire predictor is not as meaningful.

The second option for reporting odds ratios is to compare one category within each categorical predictor to another. This allows us to report the odds of collecting useful information between two specific categories of a predictor (e.g. female vs. male respondents). This is how the results will be reported in this chapter.

Each odds ratio has an associated p-value which describes the statistical significance of that odds ratio. Again, as per the standard in the social sciences, an odds ratio in this study is said to be statistically significant when $p \leq 0.05$. While an odds ratio will still be reported by the software

if the p-value is above this threshold, the results are not statistically significant. This does not mean the predictor has no impact on the outcome variable; it simply means that the model gives no indication of what the impact is.

As each odds ratio is an estimated value based on the data, each odds ratio also has an associated 95% confidence interval. This is a range of odds ratios between which we are 95% confident the actual odds ratio falls. The higher the reported odds ratio, the larger the 95% confidence interval. For simplicity, these intervals are not reported in the text of this chapter, but are included in Tables 5.2 and 5.3. Each p-value will be reported to one significant figure and the odds ratios and confidence intervals will be reported to two decimal places [311].

5.4 Results and Discussion

This data set includes a total of 264 ethnographic activities, 6050 excerpts, 6 descriptors, 18 codes, and 22,735 code applications. In this section, we will describe the results found through statistical analysis of the data.

Many of these results described here are intuitive but the value that this study provides is that it quantifies, at least for this data set, just how useful one predictor is over another in collecting information that is useful to product designers. Other results are counter-intuitive and should be considered by designers as they prepare to conduct their own ethnographic studies.

The majority of the results reported here came from one of two statistical models, the L-MH Model and the M-H Model. There are also six additional models that provide deeper insight into the results of the condition predictor. These additional models will also be described in this section.

The results of each predictor will be reported individually as the other variables in the models have been controlled for by including them in the model; this means that the results of each variable reported are independent of the effects of the other variables in model.

These results will be listed in the text, as well as in a diagram for each model and predictor. Each diagram has one of the categories within that predictor on each of the vertices. The arrows between two vertices indicate the relationship between the two and the numbers along each arrow are the odds ratio with its associated p-value in parentheses. If the arrow is pointing from Vertex 1 to Vertex 2 with an odds ratio of 2.43, it means that Vertex 2 is 2.43 more likely than Vertex 1 to

provide useful information. If there is a line instead of an arrow between two vertices, the p-value is greater than 0.05 so the odds ratio for that relationship is not statistically significant.

There is a relationship between the odds ratios in the diagrams, but this relationship is not immediately observable. As described in equations 5.2 and 5.3, a coefficient is calculated to quantify the relationship between two predictors. The coefficients (which are not reported here) are additive, meaning that if there are three categories, the first two coefficients can be added or subtracted to calculate the third. However, the odds ratios, which are reported in the text and diagrams, are calculated by taking the exponent of the coefficients. Because of the exponential function, the odds ratios are not additive but the natural logarithm of the odds ratios are additive.

After the results are listed, there is some discussion of how those results can be used by designers planning their own cross-border design ethnographies. The implications of these results will be discussed in greater depth in Section 5.

5.4.1 Influence of Condition

The condition predictor is the one that most influenced the locations chosen for this study. Some of the results for this predictor were very intuitive and some were not. In an effort to gain a deeper understanding of these counter-intuitive results, the 6 additional models were used.

As shown in Table 5.3 and Figure 5.1, the M-H Model gave the following results for the condition:

1. Having language fluency and community partners led researchers to be 5.00 ($p < 0.001$) times more likely to collect highly useful information than having only community partners
2. Having cultural familiarity, language fluency, and community partners led researchers to be 18.48 ($p < 0.001$) times more likely to collect highly useful information than having only community partners
3. Having cultural familiarity, language fluency, and community partners led the researchers to be 3.70 ($p < 0.001$) times more likely to collect highly useful information than having only language fluency and community partners

Table 5.2: Results from L-MH Model. The predictor in the first column is being compared to the predictor in the second column. For example, the first row is interpreted as “the community partners only condition is 1.50 ($p < 0.001$) times more likely to give medium or high usefulness information than the language fluency and community partners condition”

Predictor 1	Predictor 2	p-Value	Odds Ratio	95% Confidence Interval	
				Lower Limit	Upper Limit
Community Partners Only	Language Fluency and Community Partners	<0.001	1.50	1.23	1.84
Community Partners Only	Cultural Familiarity, Language Fluency, and Community Partners	<0.001	2.50	1.88	3.33
Language Fluency and Community Partners	Cultural Familiarity, Language Fluency, and Community Partners	<0.001	1.66	1.31	2.12
Interviews	Observations	<0.001	40.02	20.20	79.27
Field Reports	Observations	<0.001	3.14	2.25	4.40
Interviews	Field Reports	<0.001	12.73	6.93	23.37
Primary Sources	Secondary Sources	0.7	Not Statistically Significant		
Primary Sources	Researchers' Notes	<0.001	1.90	1.58	2.30
Secondary Sources	Researchers' Notes	<0.001	1.98	1.62	2.41
Women Only	Men Only	0.6	Not Statistically Significant		
Mixed Gender Group	Women Only	1	Not Statistically Significant		
Mixed Gender Group	Men Only	1	Not Statistically Significant		
Gender Not Applicable	Women Only	0.001	4.42	1.81	10.75
Gender Not Applicable	Men Only	0.002	4.24	1.73	10.36
Gender Not Applicable	Mixed Gender Group	<0.001	4.35	2.42	7.81
Children	Young Adults	0.01	1.93	1.15	3.25
Middle Aged	Children	0.3	Not Statistically Significant		
Seniors	Children	0.3	Not Statistically Significant		
Middle Aged	Young Adults	<0.001	1.48	1.23	1.80
Seniors	Young Adults	0.02	1.42	1.06	1.90
Middle Aged	Seniors	0.8	Not Statistically Significant		
Prototypes Used	Prototypes Not Used	<0.001	31.32	21.64	45.33
Explicit Need Statements	Implicit Need Statements	0.01	1.75	1.14	2.68

This pattern is to be expected but these results show, for this data set, just how much more effective a design team can be when they are familiar with the culture or fluent in the local language. The odds ratios indicate that the impact of language fluency is greater than the effect of cultural familiarity. They also show that the combination of cultural familiarity and language fluency have a very significant impact on the ability of the design team to collect information that is highly useful for making product design decisions.

This indicates that design teams should choose projects in locations where they have cultural familiarity and language fluency in addition to community partners whenever possible. If having both is not possible, choosing projects in locations where they have language fluency should be a priority so they can communicate directly with respondents as much as possible.

Table 5.3: Results from M-H Model. The predictor in the first column is being compared to the predictor in the second column. For example, the first row is interpreted as “the language fluency and community partners condition is 5.00 ($p < 0.001$) times more likely to give highly useful information than the community partners only condition”

Predictor 1	Predictor 2	p-Value	Odds Ratio	95% Confidence Interval	
				Lower Limit	Upper Limit
Language Fluency and Community Partners	Community Partners Only	<0.001	5.00	3.42	7.30
Cultural Familiarity, Language Fluency, and Community Partners	Community Partners Only	<0.001	18.48	10.84	31.51
Cultural Familiarity, Language Fluency, and Community Partners	Language Fluency and Community Partners	<0.001	3.70	2.28	6.00
Interviews	Observations	0.003	4.48	1.64	12.25
Field Reports	Observations	<0.001	6.62	3.44	12.76
Interviews	Field Reports	0.4	Not Statistically Significant		
Primary Sources	Secondary Sources	0.008	1.52	1.12	2.06
Primary Sources	Researchers' Notes	0.3	Not Statistically Significant		
Secondary Sources	Researchers' Notes	0.09	Not Statistically Significant		
Women Only	Men Only	<0.001	1.78	1.31	2.41
Mixed Gender Group	Women Only	0.5	Not Statistically Significant		
Mixed Gender Group	Men Only	0.9	Not Statistically Significant		
Gender Not Applicable	Women Only	0.6	Not Statistically Significant		
Gender Not Applicable	Men Only	0.3	Not Statistically Significant		
Gender Not Applicable	Mixed Gender Group	0.04	2.42	1.05	5.61
Middle Aged	Young Adults	0.03	1.45	1.04	2.02
Seniors	Young Adults	0.4	Not Statistically Significant		
Middle Aged	Seniors	0.5	Not Statistically Significant		
Prototypes Used	Prototypes Not Used	<0.001	7.79	5.81	10.46
Explicit Need Statements	Implicit Need Statements	<0.001	4.93	3.31	7.33

As shown in Table 5.2 and Figure 5.1, the L-MH Model gave the following results:

1. Having community partners only led the researchers to be 1.50 ($p < 0.001$) times more likely to collect information coded medium or high usefulness than having language fluency and community partners
2. Having community partners only led the researchers to be 2.50 ($p < 0.001$) times more likely to collect information coded medium or high usefulness than having cultural familiarity, language fluency, and community partners
3. Having language fluency and community partners led the researchers to be 1.66 ($p < 0.001$) times more likely to collect information coded medium or high usefulness than having cultural familiarity, language fluency, and community partners

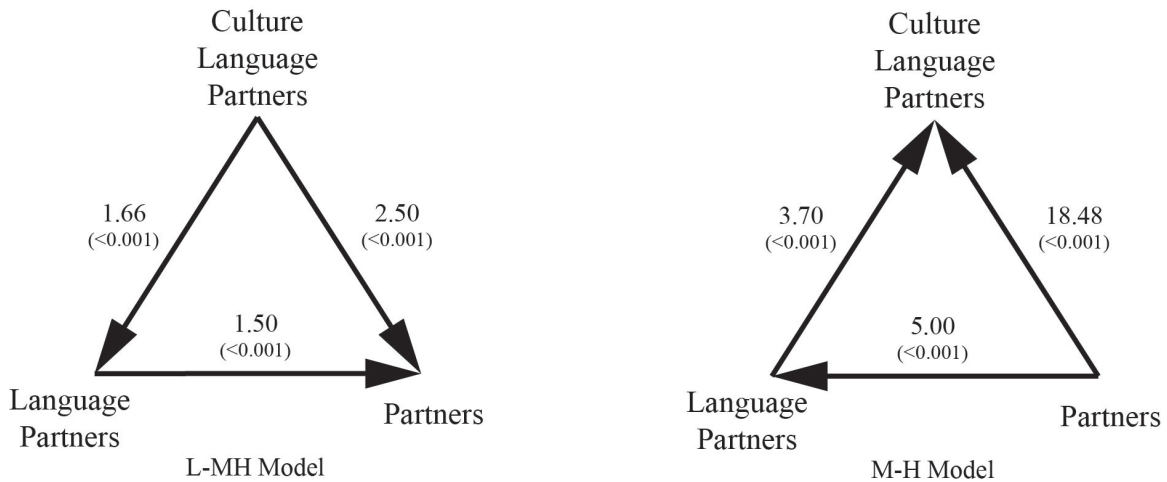


Figure 5.1: Results for condition predictor.

The pattern here is opposite of the previous model and of what was expected for the condition predictor. The results show that having community partners only is the most effective condition for collecting information coded as medium or high usefulness, followed by language fluency and community partners, and that cultural familiarity, language fluency, and community partners is the condition least likely to give information coded medium or high usefulness. This unexpected pattern may have several factors that contribute to it, one of which is undoubtedly the high number of low usefulness excerpts collected in Brazil as shown in Table 5.6. This pattern will be discussed in greater detail below.

To begin exploring other possible causes of the counter-intuitive L-MH Model results for the condition predictor, we analyzed several additional models. These additional models allowed us to test hypotheses regarding the potential causes. In the end, there were six additional models that provided deeper insight.

Additional Models 1 and 2 were similar to the L-MH Model and the M-H Model, respectively. The only difference was that the condition predictor was replaced with the country predictor in each case. The country variable was not used in either of the original L-MH or M-H Models. Additional Models 1 and 2 allow us to determine if the results from the L-MH Model were based on a country-specific affect. The condition and country predictors are the same except for 2 cases:

1. When ethnographic activities were conducted with English speakers in India, moving the activity from a community partners only condition to a language fluency and community partners condition. This affected 12% of the excerpts from India
2. When ethnographic activities were conducted in French or Kinyarwanda in Rwanda, moving the activity from the condition of language fluency and community partners to community partners only

The results for Additional Models 1 and 2 are listed in Table 5.4 and Figure 5.2. Additional Model 1 shows that the location where researchers were most likely to collect information coded medium or highly useful was Rwanda, followed by India, then Brazil, and finally Spain. Additional Model 2 shows that the location where researchers were most likely to collect highly useful information is Brazil, followed by Rwanda, and then India. There was no statistically significant odds ratio comparing Brazil and Rwanda.

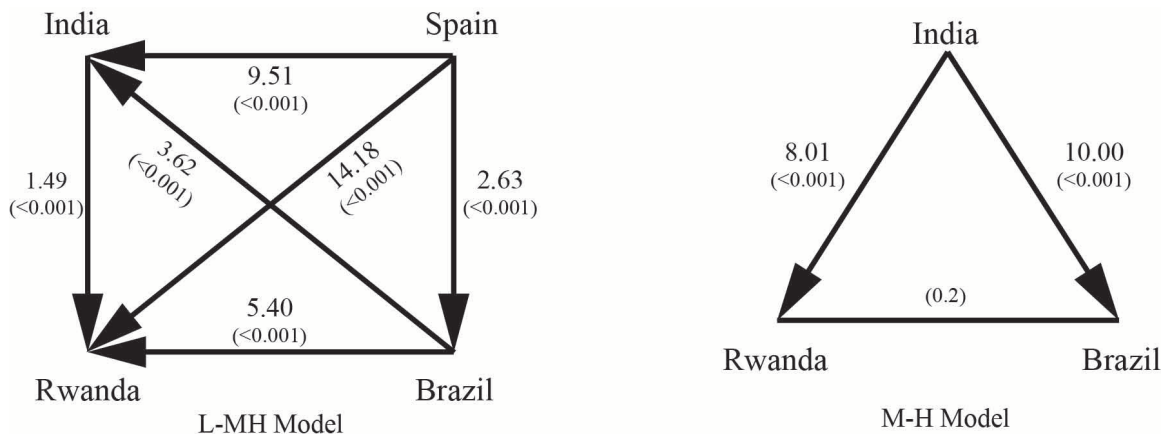


Figure 5.2: Results for Additional Models 1 and 2.

This is a different pattern than was indicated by the results of the L-MH and M-H Model using the condition predictor but still not the order we would have intuited– namely that Brazil would be the country most likely to yield useful information because the condition in that location was cultural familiarly, language fluency, and community partners. This confirmed our hypothesis that the difference was caused, at least in part, by something specific to the location.

Table 5.4: Results from Additional Models 1 and 2. These show the L-MH Model and M-H Model respectively when the condition predictor was replaced with the country predictor. The predictor in the first column is being compared to the predictor in the second column. For example, the first row is interpreted as “information collected in India is 9.51 ($p < 0.001$) times more likely to be of medium or high usefulness than information collected in Spain”

Predictor 1	Compared to Predictor 2	p-Value	Odds Ratio	95% Confidence Interval	
				Lower Limit	Upper Limit
Additional Model 1					
India	Spain	<0.001	9.51	7.11	12.74
Brazil	Spain	<0.001	2.63	1.95	3.54
Rwanda	Spain	<0.001	14.18	10.59	19.00
Rwanda	India	<0.001	1.49	1.26	1.76
India	Brazil	<0.001	3.62	2.93	4.48
Rwanda	Brazil	<0.001	5.40	4.34	6.71
Additional Model 2					
Brazil	India	<0.001	10.00	6.80	14.71
Rwanda	India	<0.001	8.01	5.70	11.25
Brazil	Rwanda	0.2	Not Statistically Significant		

Our next hypothesis to be tested related to what could have been different in each location. Surely the culture in each location had an effect. For example, in some locations the culture is more time-bound making it easier for researchers to plan their activities and keep appointments which affected their ability to collect information. But we do not have the appropriate codes to test for that particular effect. As described in Section 2, the degree to which the ethnographic study was focused on a specific problem area was different in each of the countries and this is a hypothesis we were able to test with our codes. To test this, each of the excerpts were divided into two groups: those collected during open-ended ethnographic activities and those collected during problem-area specific ethnographic activities.

The first group, open-ended ethnographic activities, included all activities in Spain, most of the activities from the first four weeks in India, activities from the first field study in Brazil, and none of the activities from Rwanda.

The second group, problem-area specific ethnographic activities, included no activities from Spain, the remainder of the activities from India, activities during the second and third field studies in Brazil, and all of the activities conducted in Rwanda.

Once the excerpts had been grouped into these two categories, Additional Models 3 through 6 were performed. The results are listed in Table 5.5. Each of these four models was analyzed first with the condition predictor, followed by the country predictor and all results are in the table.

Table 5.5: Results from Additional Models 3 through 6. This table lists results for each model with either the condition or country predictor included. The predictor in the first column is being compared to the predictor in the second column. For example, the first row is interpreted as “information collected in the community partners only condition is 3.40 ($p < 0.001$) times more likely to be of medium or high usefulness than information collected in the language fluency and community partners condition”

Predictor 1	Compared to Predictor 2	p-Value	Odds Ratio	95% Confidence Interval	
				Lower Limit	Upper Limit
Additional Model 3					
Community Partners Only	Language Fluency and Community Partners	<0.001	3.40	2.34	4.95
Community Partners Only	Cultural Familiarity, Language Fluency, and Community Partners	<0.001	6.04	3.70	9.87
Language Fluency and Community Partners	Cultural Familiarity, Language Fluency, and Community Partners	0.005	1.78	1.20	2.64
India	Spain	<0.001	4.14	2.86	6.01
Spain	Brazil	0.05	Not Statistically Significant		
India	Brazil	<0.001	6.14	3.89	9.71
Additional Model 4					
Community Partners Only	Language Fluency and Community Partners	Insufficient Number of Excerpts			
Community Partners Only	Cultural Familiarity, Language Fluency, and Community Partners	Insufficient Number of Excerpts			
Language Fluency and Community Partners	Cultural Familiarity, Language Fluency, and Community Partners	Insufficient Number of Excerpts			
Brazil	India	Insufficient Number of Excerpts			
India	Rwanda	Insufficient Number of Excerpts			
Rwanda	Brazil	Insufficient Number of Excerpts			
Additional Model 5					
Language Fluency and Community Partners	Community Partners Only	<0.001	1.59	1.26	2.00
Cultural Familiarity, Language Fluency, and Community Partners	Community Partners Only	0.001	1.70	1.23	2.34
Cultural Familiarity, Language Fluency, and Community Partners	Language Fluency and Community Partners	0.7	Not Statistically Significant		
Brazil	India	0.06	Not Statistically Significant		
Rwanda	India	0.2	Not Statistically Significant		
Brazil	Rwanda	0.3	Not Statistically Significant		
Additional Model 6					
Language Fluency and Community Partners	Community Partners Only	<0.001	5.73	3.90	8.44
Cultural Familiarity, Language Fluency, and Community Partners	Community Partners Only	<0.001	12.75	8.27	19.67
Cultural Familiarity, Language Fluency, and Community Partners	Language Fluency and Community Partners	<0.001	2.22	1.54	3.21
Brazil	India	<0.001	13.22	8.58	20.38
Rwanda	India	<0.001	7.75	5.24	11.47
Brazil	Rwanda	0.006	1.71	1.16	2.50

- Additional Model 3 is the L-MH analysis of the open-ended ethnography data
- Additional Model 4 is the M-H analysis of the open-ended ethnography data
- Additional Model 5 is the L-MH analysis of the problem-area focused ethnography data
- Additional Model 6 is the M-H analysis of the problem-area focused ethnography data

As shown in Figure 5.3, the results of Additional Model 3 indicate that when design teams begin with an open-ended ethnography, they are most likely to collect information coded medium or high usefulness in a the condition of community partners only, followed by the condition of language fluency and community partners, and least likely to collect information coded medium or high usefulness in the condition of cultural familiarity, language fluency, and community partners. This is the same order as the original L-MH Model.

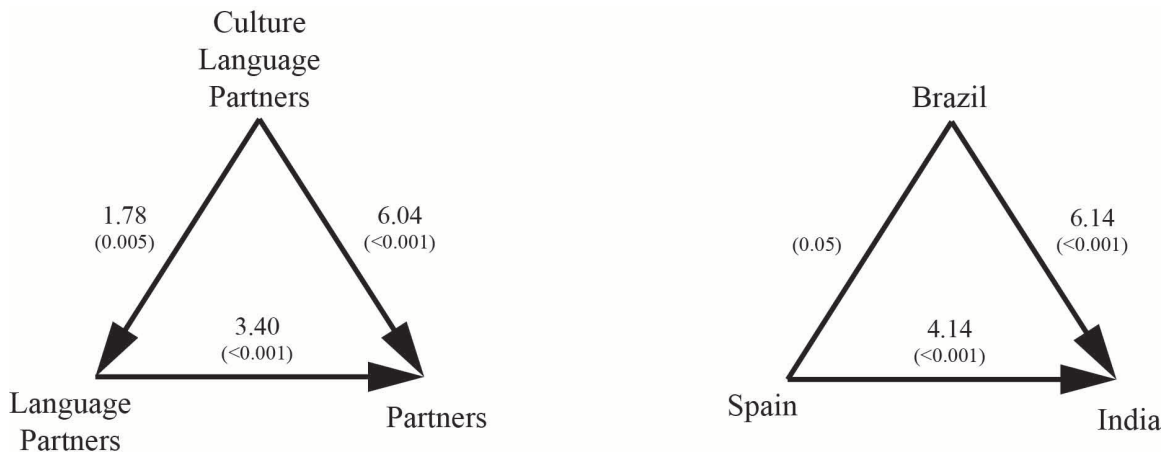


Figure 5.3: Results for Additional Model 3 – L-MH analysis of the open-ended ethnography data for condition and country predictors.

The condition of community partners only may be the most likely to provide useful information because this is the only condition that requires a translator. The information collected through a translator in this study was not recorded and transcribed word-for-word; the information was translated on the spot and recorded by the researchers. This means that the translator heard all of the responses from members of the community and had to immediately choose which responses

Table 5.6: The number of excerpts in each category of usefulness by country.

	Spain	India	Brazil	Rwanda
Low Usefulness	709	749	1,256	772
Medium Usefulness	72	589	357	632
High Usefulness	0	124	479	311

to translate. The translator made these decisions based on what he thought would be of most interest to the researchers and in this process, much of the less useful information was not translated and recorded by the researchers. This means that statements respondents made were not recorded and included in the analysis which helps explain the results from Additional Model 3.

Without a translator to filter the less useful information, the researchers in the cultural familiarity, language fluency, and community partners condition were exposed to more information— a large portion of which was low on the scale of usefulness for making product design decisions as shown by Table 5.6. The increased amount of information collected and the lack of an external filter meant that the researchers recorded a higher amount of low usefulness information. This decreases the numerator in the odds ratio equation for the condition of cultural familiarity, language fluency, and community partners, lowering the odds ratio for this predictor as shown by Additional Model 3.

As shown in Figure 5.4, several of the predictors were collinear in Additional Model 4 and were removed from the model by the software. After removing the collinear predictors, there were an insufficient number of excerpts remaining to conduct a statistically significant analysis so there are no results from this model.

The results from Additional Model 5, shown in Figure 5.5, indicate what we would expect: that having cultural familiarity, language fluency, and community partners is the condition in which researchers are most likely to collect information coded as medium or high usefulness for product design, followed by the language fluency and community partners condition, followed lastly by the community partners only condition.

It is instructive to note that, while Additional Model 5 follows this pattern, the odds ratios indicate that the differences between the conditions are relatively small. This means that for this

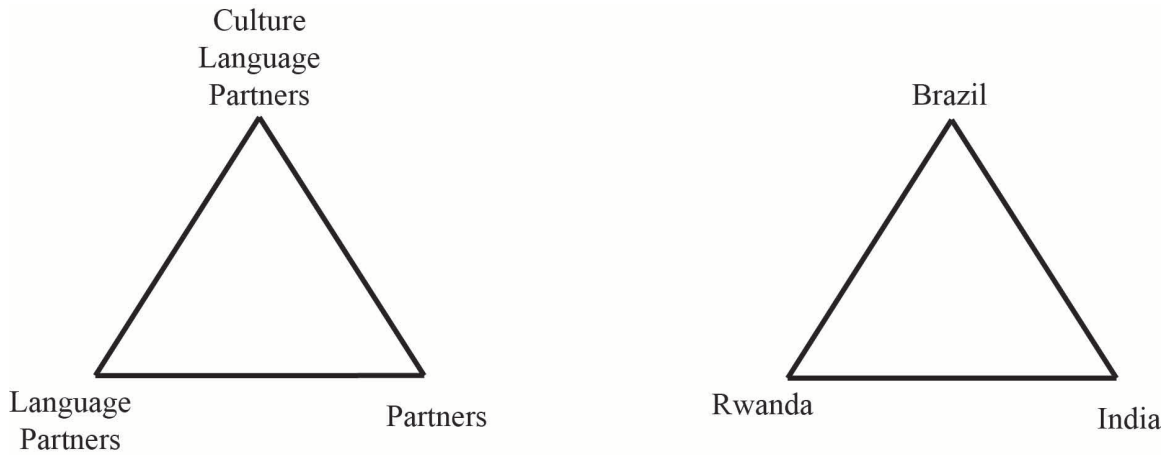


Figure 5.4: Results for Additional Model 4 – M-H analysis of the open-ended ethnography data for condition and country predictors. There were insufficient data to run this model.

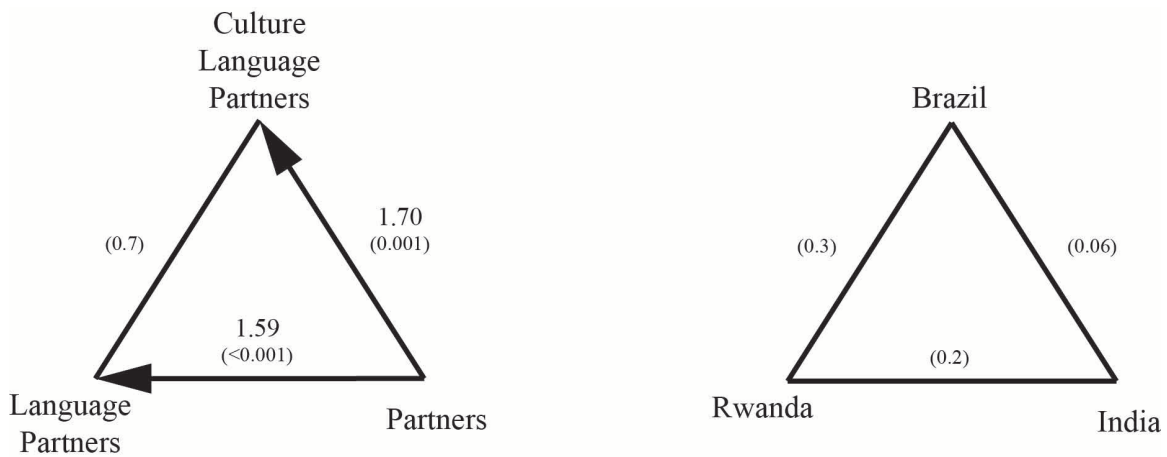


Figure 5.5: Results for Additional Model 5 – L-MH analysis of the problem-area focused ethnography data for condition and country predictors.

data set, design teams with cultural familiarity and language fluency did not have a large advantage over teams with only community partners in collecting information that was coded as medium or high usefulness.

The results for Additional Model 6, shown in Figure 5.6, indicate the same pattern but the odds ratios are much higher, indicating that design teams with cultural familiarity and language fluency *did* have a distinct advantage when it came to collecting information that was highly useful for making product design decisions. These results together indicate that designers conducting

problem-area focused ethnographies in conditions where they have only community partners will still be able to collect useful information, but they will lack the ease of communication that facilitates the collection of *highly useful* information. This may cause designers to make assumptions to fill in gaps in their understanding of customer needs which often leads to less desirable products.

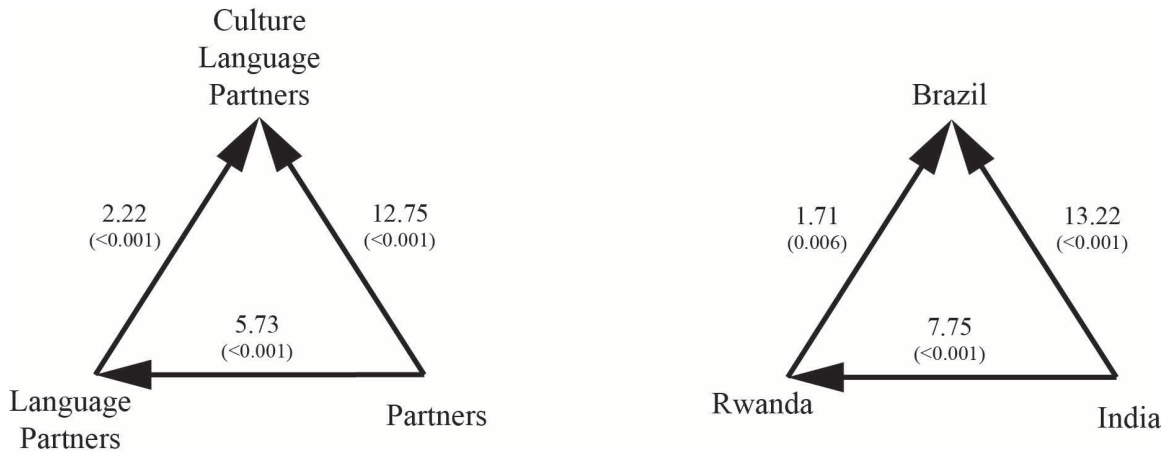


Figure 5.6: Results for Additional Model 6 – M-H analysis of the problem-area focused ethnography data for condition and country predictors.

The six additional models provided a greater understanding of the effects of the condition predictor on the ability of the researchers in this study to collect information that is more highly useful. The results of Additional Models 1 and 2 make it clear that the counter-intuitive results were caused by some factor specific to each location and Additional Models 3 through 6 make it clear that a significant factor was the degree to which the researchers were focused on a specific problem area during their ethnographic study.

All of the results shared in the remainder of this section are from the L-MH and M-H Models. We chose to use these models because they include all of the data and because they give the broadest patterns for assisting design teams planning their own cross-border design ethnographies.

5.4.2 Influence of Ethnographic Activity

We started with a set of four ethnographic activities to test: interviews, observation, participation, and community maps. As described in Section 1, participation and interviews were

combined into a single category and community maps was excluded from the analysis because so few excerpts were collected through this activity. Another activity, field reports, was added to the list after the analysis showed that a significant amount of information was collected through these reports. This leaves three activities in the final analysis: observations, interviews, and field reports, as shown in Figure 5.7. The influence of the ethnographic activity predictor from the L-MH Model are:

1. Interviews were 40.02 ($p < 0.001$) times more likely to result in information that was coded medium or high usefulness than observations
2. Field reports were 3.14 ($p < 0.001$) times more likely to result in information that was coded medium or high usefulness than observations
3. Interviews were 12.73 ($p < 0.001$) times more likely to result in information that was coded medium or high usefulness than field reports

The influence of the ethnographic activity predictor shown by the M-H Model are:

1. Interviews are 4.48 ($p = 0.003$) times more likely to result in highly useful information than observations
2. Field reports are 6.62 ($p < 0.001$) times more likely to result in highly useful information than observations
3. There is no statistically significant result comparing interviews and field reports for collecting highly useful information ($p = 0.4$)

A count of the excerpts in each category of usefulness for each country is given in Table 5.7.

These results show that, for this data set, conducting interviews is by far the activity that is most likely to lead to useful information. Interviewing is also the activity that provided the bulk of the excerpts. This activity was most common in part because it was the least formal. In each community, people were generally willing to talk with researchers but were less willing to show them into their homes or host an event they could participate in. Interviews required the least amount of the respondent's time, energy, or planning and were therefore the most common way for respondents to engage with the researchers.

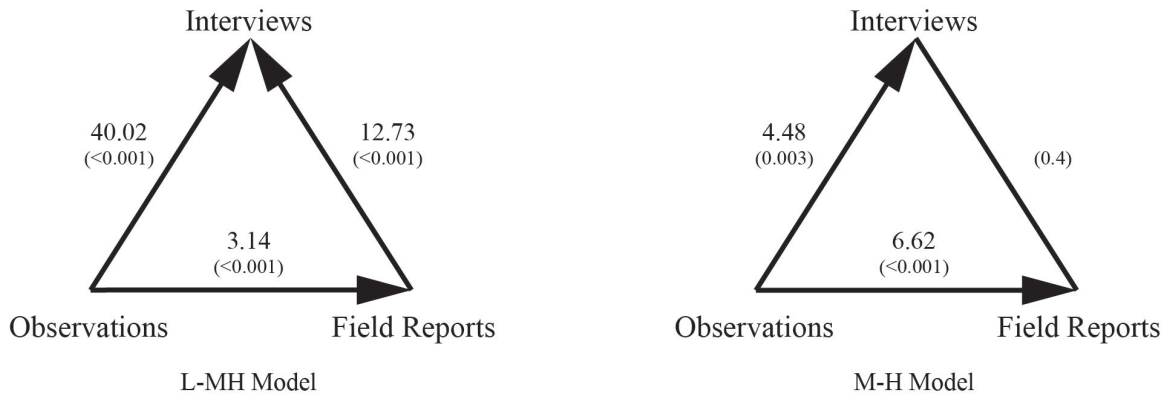


Figure 5.7: Results for the ethnographic activity predictor.

Table 5.7: The number of excerpts in each category of usefulness by ethnographic activity.

	Community Maps	Observations	Interviews	Field Reports
Low Usefulness	13	361	2,198	914
Medium Usefulness	0	69	1,357	224
High Usefulness	0	25	770	119

Field reports took significant effort to generate but they were helpful to the researchers in two ways: first, recording the events of the day forced the researchers to be aware of how the ethnographic study was being conducted, which things were working well and which weren't. This analysis allowed the researchers to make more conscious decisions about their ethnographic activities. Second, it was a way for researchers to process and synthesize the information they were collecting. Field reports can allow the designers to clearly see what has been learned and what the next most pressing questions are.

Observations provided no interaction with people and was the activity that led to the least useful information, indicating that the interaction with people in a community is the essential factor for collecting more highly useful information. But observations should not be completely discounted. Observations of the community in general helped researchers become familiar with the context. These observations were particularly useful during the first few days of each study but

these observations were too broad and unfocused to be useful for making product design decisions. Researchers found that using observations was effective again after they had a specific problem area to focus on. Observations of someone solving the problem in the traditional way or of using a prototype did lead to information that was useful in making design decisions. Much can be learned from observing the differences between what people say and what they do [61] and these observations can only be made in the field.

These results from this study clearly indicate that if the team has limited time in the field, interviews are the most efficient ethnographic activity for collecting information that will be useful for product design decisions. Design teams should consider that there is some information that can not be acquired through interviews (e.g. observing differences between peoples' words and actions) so a variety of ethnographic activities should still be planned for. In addition, keeping a field report allows the designers to record information that is useful for product design and allows them make more conscious decisions about how to conduct their ethnographic study as they spend time in the field.

5.4.3 Influence of the Source of Information

There are three sources that were analyzed in this study: primary sources, secondary sources, and researchers' notes. The effect of source as shown by the L-MH Model are:

1. Primary sources are 1.90 ($p < 0.001$) times more likely to provide information that was coded medium or high usefulness than researchers' notes
2. Secondary sources are 1.98 ($p < 0.001$) times more likely to provide information that was coded medium or high usefulness than researchers' notes
3. There was no statistically significant result comparing primary and secondary sources for likelihood of providing information of medium or high usefulness ($p = 0.7$)

The effect of source as shown by the M-H Model are:

1. Primary sources were 1.52 ($p = 0.008$) times more likely to provide information that was highly useful than secondary sources

2. There was no statistically significant result comparing primary sources and researchers' notes for likelihood of providing highly useful information ($p = 0.3$)
3. There was no statistically significant result comparing secondary sources and researchers' notes for likelihood of providing highly useful information ($p = 0.09$)

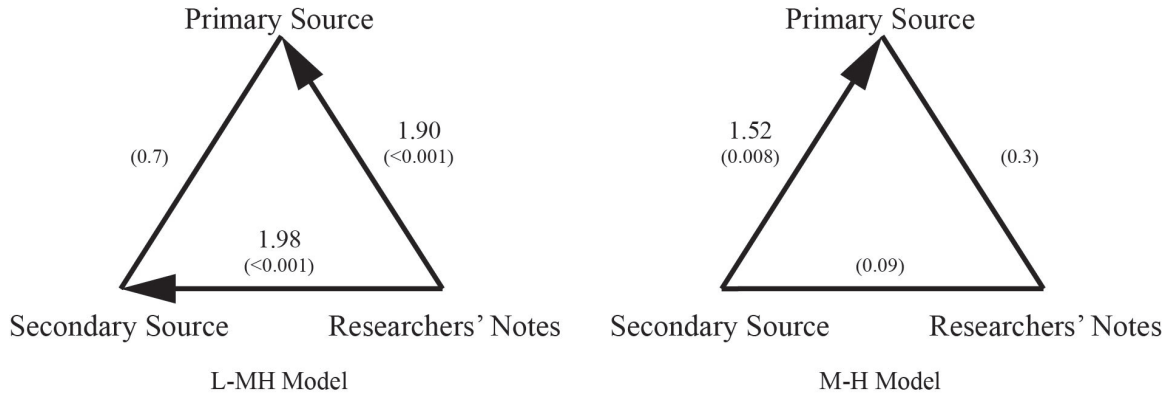


Figure 5.8: Results for the source predictor.

These results from the L-MH Model, also shown in Figure 5.8, indicate that both primary and secondary sources were more likely to provide information of medium or high usefulness than researchers' notes. The results from the M-H Model indicate that primary sources are more likely to give highly useful information than secondary sources. This means that talking with someone about their own situations or talking with someone about another person's situation are almost equally likely to result in useful information, but that highly useful information is more likely to come from talking with someone about their own experience.

The results of the L-MH Model also show the importance of interactions with members of the community, as both primary and secondary sources are more likely to provide more highly useful information than researchers' notes. But there was still highly useful information collected through field reports. These notes are a useful source of information because they are made as the researchers synthesize the information they are collecting from people. This synthesis is a necessary step in concluding what the customer needs are and how the information collected will affect design decisions for the product.

5.4.4 Influence of Gender

Gender was another predictor that had an impact on the researchers' ability to collect useful information. As shown in Table 5.8, a higher number of the total ethnographic activities involved men, less involved women, and significantly less involved a situation where gender was not applicable (such as in observations and field reports) or a mixed gender group. The L-MH Model provides the following results:

Table 5.8: Percentage of ethnographic activities completed by each gender group.

Gender Group	Percentage of Activities
Men	42.3%
Women	38.4%
Not Applicable	10.6%
Mixed Group	8.8%

1. There was no statistically significant result comparing women to men for collecting information coded medium or high usefulness ($p = 0.6$)
2. There was no statistically significant result comparing mixed gender groups to either women alone ($p = 1$) or men alone ($p = 1$) for collecting information coded medium or high usefulness

The M-H Model provides the following results:

1. Women were 1.78 ($p < 0.001$) times more likely to give highly useful information than men
2. There was no statistically significant result comparing mixed gender groups to either women alone ($p = 0.5$) or men alone ($p = 0.9$) for collecting highly useful information

The number of excerpts in each category of usefulness by gender group are listed in Table 5.9.

Table 5.9: Number of excerpts from each gender by usefulness.

	Gender Not Applicable	Women	Men	Mixed Gender Group
Low Usefulness	1,193	833	1,266	194
Medium Usefulness	286	578	526	260
High Usefulness	144	227	246	297

As shown in Figure 5.9, most of the results for this predictor in both models were not statistically significant. This does not mean that gender has no impact on the researchers' ability to collect useful information; it simply means that the model cannot tell us what that impact is.

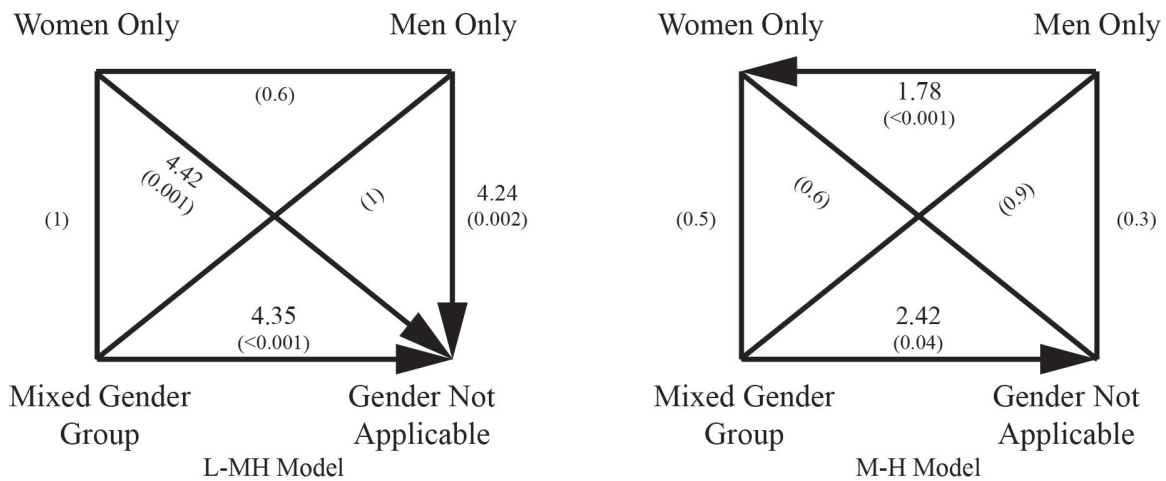


Figure 5.9: Results for the gender predictor.

The results that were statistically significant in the M-H Model indicate that women are more likely than men to provide useful information. Because women are more affected by poverty alleviation efforts than men [42] and because they are more likely to provide highly useful information, design teams should carefully consider the gender balance that will most benefit their ethnographic study.

We believe that more of the activities were completed by men in this data set because of the six researchers involved, four are men. The researchers made an effort to keep a balanced

group of respondents but it was more comfortable and often more culturally appropriate for men to speak with other men individually than with women individually. While the researchers in this particular experiment could have sought out more female respondents for ethnographic activities, the fact remains that this is not an uncommon occurrence for design teams conducting cross-border ethnographies.

There are several social factors influencing this imbalance. One is that engineering in the US is a male-dominated profession. The US Department of Commerce reported that only 14% of professional engineers were women [312]. This means that men are likely making up the majority of the design teams conducting field studies. The second factor is that developing communities typically have more traditional, formal, and patriarchal cultural contexts. These factors combined make it difficult for design teams to access female respondents.

Design teams can overcome this challenge by: (i) including more female engineers in the field study to conduct the ethnographic activities, and (ii) by more actively seeking female respondents for those activities. The results from this data set show that female respondents are more likely to provide information that is highly useful for product design decisions so it is worth the extra effort that may be required to interact with them.

5.4.5 Influence of Age

The age of respondents in the ethnographic activities also influenced the ability of the researchers to collect useful information. The results from the L-MH Model show:

1. Middle aged respondents were 1.48 ($p < 0.001$) times more likely to provide information coded as medium or high usefulness than young adults
2. Seniors were 1.42 ($p = 0.02$) times more likely to provide information coded as medium or high usefulness than young adults
3. Children were 1.93 ($p = 0.01$) times more likely to provide useful information than young adults
4. There was no statistically significant result comparing seniors to middle aged respondents ($p = 0.8$) for providing information coded as medium or high usefulness

- There was no statistically significant result comparing children and middle aged respondents ($p = 0.3$) or seniors ($p = 0.3$) for providing information coded as medium or high usefulness

The M-H Model shows:

- Middle aged respondents are 1.45 ($p = 0.03$) times more likely to provide highly useful information than young adults
- There was no statistically significant result comparing seniors to either young adults ($p = 0.4$) or to middle aged respondents ($p = 0.5$) for providing highly useful information

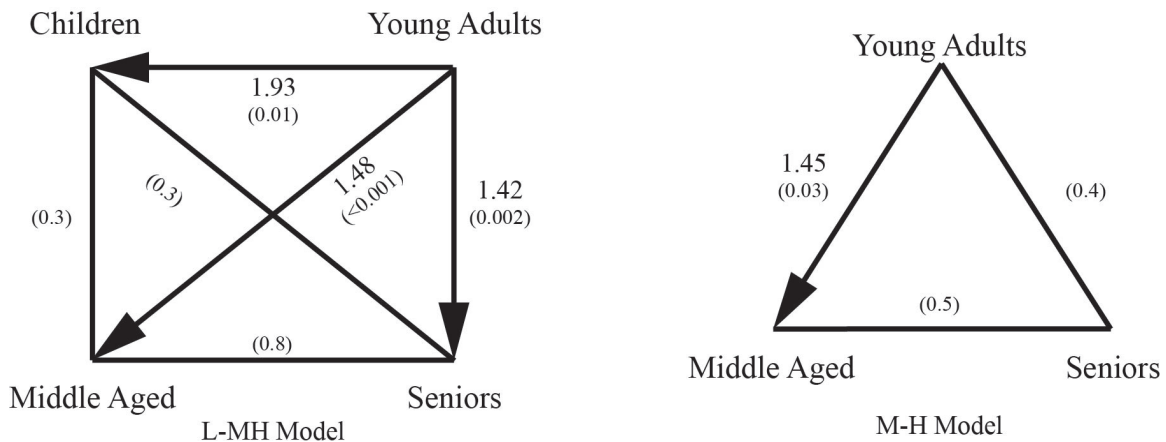


Figure 5.10: Results for the age predictor.

As shown in Table 5.10, this predictor also provided only a few statistically significant results. The results do indicate that, while useful information was collected from individuals in each age category, middle aged respondents as a group were most likely to provide information that was highly useful for product development decisions. They also indicate that young adults were the group least likely to provide useful information.

The decision of which age group the design team engages with may depend on the type of product being designed and the intended customers for that product. Generally, respondents from a variety of age groups should be involved in ethnographic activities because each age group will have a different perspective and different insights that may be helpful to product designers.

5.4.6 Influence of Prototypes

For the communities in India, Brazil, and Rwanda, physical prototypes were used to collect feedback from respondents in the field. No prototypes were used in Spain. These prototypes included early-stage physical products, but also simple prototypes like sketches, photos, and videos.



Figure 5.11: Results for the prototype predictor.

As seen in Figure 5.11, the results from the L-MH Model show that when prototypes of any kind were used, the researchers were 30.32 ($p < 0.001$) times more likely to collect information coded as medium or highly usefulness than when no prototypes were used. The M-H Model shows that when prototypes were used, the researchers were 7.79 ($p < 0.001$) times more likely to collect highly useful information than when no prototypes were used. It is intuitive that prototypes would facilitate the the collection of information coded as medium or high usefulness, but the extent of the influence prototypes had in this study was surprising. This indicates that prototypes are not just a good idea, they should be an integral part of the design ethnography. While it often takes significant effort and resources to either bring prototypes into the community or to build them in the community, this effort is worthwhile because of the usefulness of information it is possible to collect with the prototypes.

Design teams should use prototypes, even simple ones like sketches and mock-ups, as often as possible to facilitate the collection of more highly useful information.

5.4.7 Need Statements

While interacting with respondents, the researchers found that some respondents would state needs explicitly while others stated needs implicitly. The results of the L-MH Model show that needs stated explicitly are 1.75 ($p = 0.01$) times more likely to be coded as medium or high usefulness than needs stated implicitly. The M-H Model shows that needs stated explicitly were

4.93 ($p < 0.001$) times more likely to be highly useful than needs stated implicitly, as shown in Figure 5.12.



Figure 5.12: Results of the need statement predictor.

While both explicit and implicit needs can be useful in making product design decisions, the results show that, for this data set, explicit need statements were more likely to be coded as medium or high usefulness. The two factors that seem to have affected the way a need was stated are prototypes and gender. With prototypes, both the researcher and respondent are looking at a physical object so it is more natural for the respondent to state needs explicitly.

As shown in Table 5.10, women were significantly more likely to state their needs explicitly. These explicit needs were coded as higher usefulness, which is another reason design teams should seek out female respondents as they conduct their ethnographic studies.

Table 5.10: Number of excerpts in each need statement category by gender group.

	Women	Men	Mixed Gender Group	Gender Not Applicable
Non-Need Statement	1,029	1,372	426	1,454
Implicit Need Statement	519	542	151	157
Explicit Need Statement	109	105	174	12

5.5 Conclusions

This chapter reported on an experiment using cross-border design ethnography in four countries on four continents. Each location provided different situations that allowed us to quan-

tify the influence of several predictors on the researchers' ability to collect useful information for making product design decisions. Information collected by researchers during the field studies was coded and several statistical analyses were performed. The predictors that yielded meaningful results include cultural familiarity, language fluency, ethnographic activity used, information source type, gender and age of the respondents, use of prototypes, and type of need statements. Some of the results are intuitive but all results are quantified using odds ratios which allows us to clearly identify the impact of one predictor over another for this data set.

The results show that cultural familiarity and language fluency have a significant impact on the researchers' ability to collect useful information. When design teams are doing ethnographic studies where a problem area has not yet been identified, the results show it can be advantageous to choose a translator. The translator may be able to filter out the bulk of the less useful information and provide the team with the pieces of information that are most pertinent to their design decisions.

On the other hand, when a problem area has been specified, the results indicate that design teams should choose projects where they have both cultural familiarity and language fluency as this is the condition that is 12.75 times more likely to lead to highly useful information than with community partners only. When this is not possible, design teams should prioritize projects where they are fluent in the local language, as this makes them 5.73 times more likely to collect highly useful information than community partners alone. Language fluency was shown to have a greater impact than cultural familiarity which indicates that being able to communicate directly with respondents facilitates the collection of highly useful information for product design decisions.

Design teams can use these results to strategically select projects based on their cultural familiarity and language fluency. They can also use these results to strategically form a design team that will give them a higher likelihood of collecting useful information during their ethnographic studies. In practice, there are many other factors that also influence the selection of projects and teams. In cases where conditions are not ideal, these results can help the team set expectations and optimize their ethnographic activities for whichever condition they are working in. In all conditions, design teams will be more effective at collecting useful information as they invest in strong partnerships in the community to help facilitate their ethnographic activities.

This data set showed that conducting interviews was up to 40.02 times more likely to yield useful information for making design decisions than conducting other ethnographic activities. The researchers also found that this was the most convenient way to collect information because it required the least time and effort from respondents. As design teams plan their field studies, they should note that a variety of ethnographic activities will provide a variety of information that may not be possible to collect with one activity type alone.

Once the design team is in the field, they should consider the sources they choose to engage with. This study shows that primary sources are 1.52 times more likely than secondary sources to provide highly useful information, indicating that speaking with people directly about their own experiences should be a priority for the design team. The results also show that primary and secondary sources are both more likely to provide information that is of medium or high usefulness than researchers' notes. While these notes help the design team synthesize the information they have collected and make conscious decisions about which activities to pursue and which questions to answer next, interacting with people from the location as much as possible will lead to information of higher usefulness.

Another finding was that gender has an impact on the usefulness of the information collected during a cross-border design ethnography. This data set showed that women alone were 1.78 times more likely to provide highly useful information than men alone. Women are also more impacted by poverty alleviation efforts [42] and are likely to be the users of the products being designed. Because engineering is typically a male-dominated field, design teams working on products for resource-poor individuals are typically male-dominated. Developing communities are also typically more traditional, formal, and patriarchal which further limits access to female respondents. Including female designers on the design team can facilitate increased access to female respondents as it may be more culturally appropriate to have female respondents when women are conducting the ethnographic activities. Design teams should collect information from respondents of both gender but the researchers in this study found that it took more conscious effort and planning to collect information from female respondents. Because women are more likely to give highly useful information, the team should put in the extra effort that may be required to ensure an appropriate gender balance in their group of respondents.

The results of this study also indicate that age had an influence on the usefulness of the information collected. Middle aged respondents were up to 1.48 times more likely to give useful information than other age groups. Design teams should seek a balanced group of respondents to ensure a broad range of perspectives on the problem they are trying to solve while keeping in mind that they will likely get the most useful information from middle aged respondents.

Our study showed that using prototypes to discuss possible solutions to problems increased the likelihood of collecting highly useful information dramatically (31.32 times). It is intuitive that when a community member can see a product, they are more likely to be able to say whether it meets their needs or not but the magnitude of the impact prototypes have is surprising. Design teams should not underestimate the usefulness of even simple prototypes. Sketches, photos, and videos provided researchers in this study significant and useful feedback without requiring them to build or import expensive, high-fidelity prototypes.

Needs statements that were stated explicitly were up to 4.93 times more likely to provide highly useful information than those stated implicitly. Prototypes can help facilitate explicit need statements. Women were more likely to provide needs stated explicitly, which is an additional reason for the team to seek out female respondents for their ethnographic activities.

Overall, the results of this study can help design teams as they plan their own ethnographic studies and activities. These four communities represent a small though broad sample that serves as a starting point for exploring the relationships between cultural familiarity, language fluency, partners in the community, as well as other factors like gender, age, information source type, etc. It would take an incredible amount of resources to collect enough information to draw conclusions that would be universally applicable. Increasing the sample size to include a wider variety of locations, ethnographic activities, and more respondents would lead to results that apply more generally but we believe this sample size is large and diverse enough to provide useful insight for designers planning cross-border design ethnographies.

Future work could also include refining the definitions of some of the predictors used in this study. For example, how fluent in the local language does a design team need to be to gain the benefits of interacting directly with respondents? How much time spent in a location previous to the ethnographic study is needed for the design team to gain the benefits of cultural familiarity during their study? How does the length of the study affect the researchers' ability to conduct

the ethnography? Which other ethnographic methods could be used to collect information useful for product design? Another interesting predictor that could be analyzed is time spent during the ethnographic study. Each of the field trips included in this study were a different length of time. Some guidelines for the optimal amount of time for a given set of predictors would be of great value to design teams.

CHAPTER 6. CONCLUSIONS AND FUTURE WORK

6.1 Chapter Overview

The previous chapters present the general principles and insights that we have identified from various sources. In this chapter, conclusions and the implications of these conclusions from each of the previous chapters will be outlined. Several themes have emerged throughout the work of this dissertation and those themes will be discussed in greater detail here. Potential areas of future work are also outlined. These include several natural extensions of the work presented here as well as some other suggested areas for exploration based on what we have learned as we've completed this work. There is much work to be done in this field before engineers routinely develop products that alleviate poverty. The topics for future study outlined here will not complete the work that needs to be done but they may provide useful next steps in developing the principles and techniques needed for greater impact.

6.2 Contributions

As stated in Chapter 1, the main research question this dissertation seeks to answer was: How can engineers design products that have more significant and lasting impact on alleviating poverty in the developing world? The hypothesis that was tested was that we could identify principles and insights from three main sources of experiential knowledge: (i) the engineering literature, (ii) the experiences of practitioners working in developing communities, and (iii) our own experiences applying ethnographic techniques. This hypothesis was tested in four parts:

1. A thorough review of the engineering literature [42] – To complete this part, we reviewed 234 journal articles, conference papers, technical reports, books, and other sources to identify themes in the literature regarding best practices for designing for the developing world. Nine themes emerged and were articulated as principles. These principles are each supported by

numerous sources, indicating that they are, in fact, general design principles for design for the developing world. These principles were then related to traditional design principles and found to be independent. Traditional design principles all had to do with the solution finding process, but the nine principles all related to either the context surrounding that process or to the team making design decisions in that process. The nine principles can be used by teams designing products for the developing world to guide them in making design decisions that allow for more significant and lasting impact. While other principles will surely be identified as there is more work in this area, these were the principles currently found in the literature.

2. A sampling of a broad range of unique products from practitioners' field reports [43] – To complete this part of the research, we reviewed 41 field studies. Of these, 27 were from EWB Canada's Annual Failure Reports and 14 were from field reports of our own experiences designing and implementing products in the developing world. As the failure modes for each product were analyzed, seven themes were identified and articulated as pitfalls. These pitfalls each applied to several projects, leading us to conclude that they were common for practitioners. These pitfalls, and the Design for the Developing World Canvas created in response to them, can serve as a guide to design teams developing products for resource-poor individuals. Using the list of pitfalls and the DFDW Canvas allows teams to have a more significant and lasting impact, answering a part of our research question.
3. An in-depth analysis of one product, the Village Drill [45] – This part was completed by analyzing the implementation of the Village Drill, a human-powered machine that drills bore holes for water wells. Because the organization who owns the drill, WHOlives.org, was willing to provide detailed information of their operations for the past five years, this case study provides significant insight for design teams working in the developing world. It provides a realistic time line, a sense of the resources required, and a conservative model for evaluating the impact for the implementation of a poverty-alleviating product. This is instructive for design teams attempting to do the same. These actual data can guide engineers as they plan for the long-term sustainability of their product, leading to more significant and lasting impact.

4. An experiment using ethnographic techniques to collect information pertinent to design decisions under a variety of conditions [46] – Part 4 was planned after noticing that, in the first two parts, a lack of understanding of the context and the customer were at the root of most of the failures studied. Ethnography is a tool social scientists use to gain an understanding of a culture and context. We used adapted ethnographic techniques to gain an understanding of the context and customer using the products we designed in a cross-border setting. We tested these techniques under a variety of conditions and collected a total of 6,050 pieces of data. These data were evaluated using multiple statistical analyses and all of the results shared were statistically significant. These results offer insight to design teams planning their own cross-border ethnographies and help to answer our original research question.

Many engineers have designed products for resource-poor individuals in the developing world over the last few decades. As a topic of formal research, however, this field is still in its early stages. There have been few studies that take these individual experiences and use them to identify principles that are more generally applicable. The objective of this dissertation was to begin the process of identifying these more general principles and insights in an effort to form a foundation that other engineers can build upon. As outlined in Chapter 1, the work presented here identifies principles and insights from three sources of experiential knowledge:

1. The archival engineering literature [42]
2. The experiences of practitioners working in a non-profit setting [43], [45]
3. Our own experiences as researchers in four different countries on four different continents [46]

Chapter 2 of this dissertation presents principles derived from the engineering literature and is valuable for three reasons. First, it is among the first attempts to identify and articulate general principles for design for the developing world. These principles provide a foundation for other researchers and practitioners to build upon and advance the community's understanding of this particular type of product design. Second, the publication of this work broke new ground in ASME's Journal of Mechanical Design (JMD). Previous to this publication, JMD had published a few papers that had as their main focus a more traditional mechanical engineering topic, such

as optimization techniques, that included an example related to design for the developing world. Chapter 2 of this dissertation was the first journal article published in JMD that was exclusively about design for the developing world and since its publication, there have been several others [3], [43], [286], [288]. This brings exposure of this important topic to a broader audience and provides researchers a respected platform to share their work. Third, this chapter brings together a valuable list of sources related to design for the developing world. Because this work falls under so many different names and in so many different journals, it is valuable to the community to have all of these sources in one place.

Chapter 3 presents pitfalls common in the experiences of a group of practitioners working in a non-profit capacity in the developing world and is also valuable for three of reasons. First, the chapter reviews the experiences of individual practitioners working on developing world products and analyzed the failures modes they experienced as they attempted to implement those products. The failure modes were then categorized into themes, or pitfalls, that give insight into common failure modes for projects throughout the developing world. Now that these pitfalls have been clearly articulated, they can be easily shared with other engineers and avoided. Second, articulating these pitfalls provides another set of foundational insights that engineers in the research community can build upon. Third, the chapter introduces a tool, the Design for the Developing World Canvas, that can help the design team as they develop a new product and plan for it's implementation in the developing world. This tool provides a tangible way for design teams to make conscious decisions that avoid the pitfalls, allowing them to have more impact than they might have otherwise.

Chapter 4 presents a case study based on the experiences of a single practitioner, WHO-lives.org, and a single poverty-alleviating product, the Village Drill. This case study is valuable for several reasons. First, it provides true and unembellished data from an actual organization that has had significant impact in the developing world. This provides insights that can guide other engineers in their own entrepreneurial efforts because it accurately describes the financial and time resources required to have success in an uncertain market. Second, it sets a precedent for case studies in design for the developing world literature. This study provides five years of data post market-introduction, which is significantly more than most cases available in the literature. It also establishes a format that other case studies can follow, namely describing the six areas in the DFDW Canvas. This will allow for natural comparisons between products as other cases are

published in a similar format. This case also sets the tone for impact models. We have found that often these models are overly idealized or optimistic but this case presents a conservative estimate that accounts for the uncertainty in the values used in the model, making it much more realistic. Lastly, this case represents an important collaboration between practitioners and academics. As mentioned, there are few cases like this in the literature. This is not because there are no products successfully alleviating poverty in the developing world; it is because the people implementing them are not typically the same people who publish in archival literature.

Chapter 5 presents our own experiences using ethnographic methods to collect information from potential customers under a variety of conditions. This study is valuable because it includes information from four countries on four different continents. Though four locations is a small sample size compared to the number of developing communities in the world, having a sample of four distinctly different communities in four distinctly different cultures provides a basis for comparison that is uncommon in the literature. The information collected during this study allowed us to evaluate the effectiveness of cross-border design ethnography for collecting information that is useful for making product design decisions. The work of the chapter is also valuable because it focuses on the processes we used to collect information to make design decisions about the products. We purposefully avoided details about the products designed so that we could focus on the process of collecting customer feedback. This study is also valuable because conditions affecting the process of collecting customer feedback are quantified for the first time through rigorous statistical analyses. These conditions include language fluency, cultural familiarity, gender and age of respondents, and others. The results of this study may not apply universally, but they provide insight for design teams planning their own ethnographic studies. With these results, designers will be able to make more strategic decisions about either projects appropriate for their team or about building a team appropriate for their project.

The results that emerged from these three sources of experiential knowledge are a useful starting point in the distillation of general principles and from them, several themes have emerged. These themes will be further discussed in this concluding chapter.

6.3 Conclusions from Principles Derived from the Engineering Literature

The survey of the engineering literature related to design for the developing world was comprehensive and allowed us to derive principles from that valuable source. We took what was published in the engineering literature and distilled it into nine principles that are easily accessible to design teams and that provide guidance for them that is not found elsewhere. For example, engineers in the developed world may assume that if people in developing communities had some of the conveniences that we enjoy, such as constant access to electricity, their poverty would be alleviated. Understanding principle 3, that importing technology without adapting it to the specific developing world context is ineffective and unsustainable, can help a design team change their approach. The goal may change from delivering electricity to delivering the conveniences that access to electricity provides in a contextually appropriate way. One way that is contextually appropriate in many places is solar lanterns. These lanterns may be of little use in a developed community, but have helped many resource-poor individuals escape or alleviate the pains of poverty in their own communities. While the technology of using electricity to generate light is common in both settings, the lanterns are an adaptation of the technology that is more contextually appropriate, leading to greater impact.

Another example is the fact that there has been much emphasis on developing products for rural subsistence farmers across the world. Understanding principle 4, that individuals in both urban and rural contexts can benefit from poverty alleviation efforts, may encourage the team to challenge the assumption that most people living in poverty are poor farmers. This may help them consider the needs of resource-poor individuals in urban settings, whose needs are distinctly different.

These two examples illustrate how the nine principles answer the research question. When engineers understand and apply these principles, they have an approach that enables them to have more significant and lasting impact. These principles are general. While they may not all apply to every product designed for the developing world, they should always be considered by the design team. The application of these principles will help design teams challenge their assumptions, consider the customers and context more fully as they develop solutions, and realize that lasting impact will not happen without a team with the appropriate expertise and a plan for sustaining the product long-term.

This list of principles contains all of the themes found in the current literature but we believe others will emerge. As the research community develops and matures, other literature will be published that supports new principles that will also be generally applicable. The nine principles are among the first steps in understanding the foundational principles that will guide design teams to greater success and impact.

6.4 Conclusions from Pitfalls Derived from Practitioner Field Reports

Practitioners have worked designing products for use in developing communities for decades. Chapter 3 describes a subset of those experiences that were analyzed for common failure modes. The seven common failure modes identified, articulated as pitfalls, are a useful way to pass this experiential knowledge to other design teams. This can help teams avoid the mistakes that are commonly made implementing products in the developing world. The Design for the Developing World Canvas was created in response to these common pitfalls and is a tool design teams can use to avoid them.

One pitfall is not making a plan for or developing partners for manufacturing. Considering this pitfall allows teams to consciously plan for the manufacture of their product. This will lead them to research which manufacturing techniques are available and affordable in the community and how to best interact with the necessary partners. The five other sections of the DFDW Canvas (Impact, Customer, Product, Delivery, and Revenue Model) all provide similar insight for design teams. These sections are related to the product being designed, but focus more on the program that will support the product long-term.

The pitfalls and DFDW Canvas help to answer the main research question. The DFDW Canvas facilitates team discussions that allow the team to consciously avoid the common pitfalls. It also encourages the design team to consider the strategic partners and the contextual factors for each of the six sections. These partners and contextual factors are essential to impact. Considering each section, along with partners and contextual factors for that section, encourages the team to focus not only on the product being designed, but also the system that will support that product. This combination of product and support enables engineers to have more significant and lasting impact in the developing world.

6.5 Conclusions from the Village Drill Case Study

There were several trends that emerged in Chapter 3 as we considered a broad range of products. In Chapter 4, we examined the details of the implementation of one particular product, the Village Drill. This case study reviews the impact of the Village Drill five years after its initial market introduction. In those five years, 41 drills have drilled over 1000 boreholes, 761 of which have lead to water in 15 different countries. This has provided 170,000 people with 2 million people-months for water. Manufacturing the Village Drill and drilling these boreholes has also provided 238 people with a total of 5,838 months of employment. This case study presents unobscured and unembellished facts and figures about the actual development and sustaining of a product engineered for a developing world market and setting. It also provides insight into how impact is measured and how the product is sustained after the bulk of the product development is complete.

The case study includes details related to the design of the product, but also the development of the program that supports the product, as discussed in the previous section. From this, engineers gain insight into the resources required to start a sustainable venture in a developing world setting, the amount of travel required, the partnerships required, the amount of time needed to gain market acceptance, and a way to conservatively estimate the impact of the product. One particularly valuable characteristic of this case study is that it includes actual data for the first five years of the organizations operations. Studies of this time frame are rare the literature.

This case addresses the research question by providing a benchmark that other engineers can use to gain insight for the implementation of their own products in the developing world. It is not a list of steps to follow for successful implementation, but rather an in-depth analysis of how one particular product successfully alleviates poverty across 15 countries. This helps engineers implement products with more lasting impact because it provides insight into the resources required and the necessity of building an organization to sustain the product long-term. It also provides insight for measuring impact and how the continuous measurement of the impact of the product can help guide decisions related to the product and the organization that supports it. This leads to improvement and even more significant impact over time.

6.6 Conclusions from the Experiment in Cross-Border Design Ethnography

A common theme in all of the previous work is a lack of understanding of customers and contexts. Many in the literature and in the field reports cited a lack of this knowledge as a cause of failure, but there were few solutions to be found in the engineering literature. Large businesses have attempted market research in the developing world, or emerging markets [5]. This market research provides useful information, but typically focuses just on what products people are willing to buy and not necessarily which products will alleviate poverty. Companies focusing on emerging markets typically sell consumables— food, health and beauty products, etc. [5]. While notable exceptions exist, including mobile phones and solar lanterns, little market research has been conducted and reported for products in the developing world that require mechanical design.

Another method for determining customer needs is called ethnography. Social scientists use ethnography to develop a deeper understanding of a culture and people. A few engineering researchers have reported using ethnographic techniques to understand the customer and context and improve the cultural acceptability of their products. These reports focus on the product designed or the information collected and not on the process of using ethnography.

In Chapter 5, we report on our experiment using cross-border design ethnography and focused on the process rather than the products. This experiment was conducted in four countries on four continents under a variety of conditions. These conditions include cultural familiarity, language fluency, partners in the community, gender, age, information source type, and others. After rigorous statistical analysis, we were able to draw conclusions about how the conditions of the ethnographic study affect the usefulness of the information collected.

These results also answer the main research question because they provide insight for design teams as they plan their own ethnographic studies and activities. They can help teams understand the influence of these conditions and strategically choose either the products they should pursue based on their team or choose the members of their team based on the conditions surrounding their product. The results enable teams to plan a more effective field study to collect information about the context and customer. If the team allows their findings to inform their design decisions, they will be more likely to develop products that have significant and lasting impact.

6.7 Understanding Context

The majority of the failed products studied throughout this research follow a pattern: products in the developing world typically don't fail because of poor engineering, they typically fail because of a poor understanding of the context. For example, the challenge is not in calculating the internal reaction forces of beams in a low-cost housing structure; it's in understanding the environment (social, political, physical, financial, emotional) that will be required for the housing to be valued by resource-poor individuals. When engineers understand the context, they are better able to make design decisions for the specific environment and have greater impact.

This is shown through several of the principles from Chapter 2 and the pitfalls from Chapter 3. Design teams often work on products intended to be used in locations they are unfamiliar with, meaning they don't always understand the physical conditions in which the product they are designing will be used. Understanding these physical conditions may lead to additional design requirements that lead to better engineering decisions, making the product more successful at alleviating poverty. But more importantly, a lack of familiarity with the location can mean that the team doesn't understand the forces around the use of that product that will have an affect on it's acceptance rate, long-term maintenance, and other factors that will determine the product's impact. These forces include social, cultural, political, financial, emotional, and geographic factors. These factors are much more difficult to quantify and develop engineering requirements for, but they are often the factors that will determine the success or failure of a product.

The history of a community also has an influence. In most communities, the design team will not be the first group of Westerners attempting to improve the living conditions of that place. Understanding which other groups have worked in the community, how they operated within the community, and the impact they have had previously will help the design team interact with the community in the most appropriate way.

Chapter 4 presents a case study that illustrates some important changes made as WHO-lives.org's understanding of the context increased. Chapter 5 describes the process of cross-border design ethnography that can be used to improve the design team's understanding of the context. Improving this understanding will typically lead to more empathic, more culturally-appropriate design decisions and lead to more successful products.

6.8 Understanding Customer Needs

Most engineering design texts describe a stage at the beginning of the design process dedicated to identifying opportunities [47], [104], [313], [314], but these design texts focus mainly on the stages of product development that come after that. IDEO's Human Centered Design (HCD) Toolkit [61] is one of the few resources focused specifically on determining customer needs in a developing world context. It consists of three sections: Hear, Create, and Deliver. These sections focus on understanding the customer needs, as well as developing an effective business model for delivering solutions to the customer. It is a useful tool for designers, NGOs, and other groups who want to solve problems in developing communities and applies to product development as well as business and software solutions to problems.

As a product moves through the development process, engineers typically use a list of performance measures to evaluate the design. Once a list of performance measures has been generated, engineers are well trained in designing a product that will meet those measures. One of the most difficult parts is determining actual customer needs that lead to accurate performance measures. When engineers lack information about customer needs, they are forced to rely on assumptions to move forward with the design [33]. When the needs are based on unvalidated assumptions, the performance measures are consequently weak and designing a product to meet these weak performance measures typically leads to product failure [65], [108]. It has been shown here that cross-border design ethnography is a useful tool in collecting information from potential customers about actual needs, which can lead design teams to more impactful solutions.

Determining accurate customer needs may also be facilitated by considering three phases of determining needs. These three phases are Opportunity Focused, Problem Area Focused, and Solution Focused [315]. The engineers' involvement may begin in any of the three stages depending on the conditions of the project. No matter the starting point, the list of customer needs will progress through the end of the third stage.

As design teams gain a deeper understanding of the context, they are able to collect information that will help them pass through these three stages of determining customer needs. As the team passes through these stages, they should focus on collecting feedback from potential customers and using that feedback to inform their list of requirements. Once the requirements for a product have been refined through these stages, the design team can develop performance mea-

asures that can guide design decisions, increasing the likelihood of meeting actual customer needs and successfully alleviating poverty. The principles and insights in this work can assist teams in this process.

6.9 The Need for Partnership

Several of the principles and insights identified through this work are related to appropriate partners. Design teams analyzed here seem to make two assumptions that hinder their progress: (i) that if they can just design a product that solves a problem, poverty will be alleviated and (ii) that, because they are problem-solvers, they can figure out how to do the other work required to sustain a product, for example manufacturing, distribution, marketing, sales, and impact evaluation. The first assumption ignores the context and the structure that must be established to support a product. Whether the product is given away or sold, there are other pieces that must come together for the product to have a lasting impact. Several of these other pieces are parts of the DFDW Canvas. The second assumption was a common one in the implementation of products studied in Chapter 3. Engineers often assumed that because they were good at solving problems, they could figure out how to implement a business model or figure out how to evaluate the impact of the product they are working on. While this may be true in some situations, these cases show having strategic partners who have expertise in those areas will allow the team to be more effective and to reach a greater number of developing world customers.

The case of the Village Drill showed this clearly. The drill had a significantly broader impact when WHOlives.org partnered with local manufacturers, with local people to deliver the drills and provide initial training, and professional drillers to find drilling sites that would most likely lead to water. If they had tried to learn each of these parts and do them all in-house, they would not have scaled as quickly or been as effective as they were in their first five years.

Engineers wanting to have an impact in the developing world must invest resources in building strong and strategic partnerships in the areas where they lack expertise. As they build a team with the varied expertise that is needed to support their product, that product will have a greater impact on the lives of those living in poverty.

6.10 Future Work

The research presented in this dissertation has exposed many other gaps in the literature that need to be filled before we as engineers are routinely effective at designing for the developing world. Some of the most obvious next steps are adding to the lists of principles and pitfalls. This could be done through a continued study of more recent engineering literature, through the experiences of other practitioners in the NGO sector, or through additional field studies conducted by individual researchers. Each of these sources of experiential knowledge has been explored in this dissertation and could be added to.

Another extension of the work described in this dissertation could be to test the principles and pitfalls. They are derived from experiences found in the literature and a small group of practitioners. We have anecdotal evidence that they lead to greater impact, but they have not been formally or rigorously tested. The Design for the Developing World Canvas could also benefit from more rigorous testing. Such testing will lead to refinements of and additions to the principles, pitfalls, and Canvas that will make them more useful tools for engineers.

Future work could also include refining the definitions of some of the predictors used in the study described in Chapter 5. For example, how fluent in the local language does a design team need to be to gain the benefits of interacting directly with respondents? How much time spent in a location previous to the ethnographic study is needed for the design team to gain the benefits of cultural familiarity during their study? Which other ethnographic methods could be used to collect information that is useful for product design? Another interesting predictor that could be analyzed is time spent during the ethnographic study. Each of the field trips included in this study were a different length of time. Some guidelines for the optimal amount of time for a given set of predictors would be of great value to design teams.

Another area of experiential knowledge to explore is the private sector. While there may be others, starting with one of four groups within that sector may be helpful:

1. Multinational corporations such as Nokia, Johnson & Johnson, Microsoft, and others. These organizations have had some success in emerging markets and there are general principles and insights that can be gleaned from their experiences that have not yet been identified in the engineering literature

2. Smaller companies such as d.light, D-Rev, Design That Matters, Burn Design Lab, Burro, and others. These product-based companies have experience sustainably selling their products in developing communities and have experience that could offer significant insight for the engineering community
3. Design firms that provide design services for developing world products such as Catapult Design and others. These firms would have experience in many different contexts that may lead to principles and insights that have not yet been identified
4. Local entrepreneurs in developing communities. Much could be learned from individuals who grew up in developing communities and who have designed products that alleviate poverty. These individuals may be hard to find but surely, among all of the developing communities of the world, there are individuals who have done this successfully without the help of Westerners. Their experience would be an extremely valuable addition to the engineering literature

Along with the fourth category, future work could include product development education tailored to members of developing communities. This could include teaching the product design process and supporting individuals as they develop products to solve the problems they see in their own communities. When members of these communities are enabled to design their own products, they naturally bring an understanding of the context and needs into the process and that may lead to more impactful solutions. Amy Smith at MIT has started a program called Creative Capacity Building with the goal of providing this education. Her work could be extended by developing educational materials for different cultural contexts or experimenting with new methods for providing the ongoing support that may be needed.

Educational modules could also be developed for translators from developing communities working with design teams. A translator from the local community will be able to interact in a more culturally-appropriate way and will understand the local context but without a basic knowledge of the design process, they may not understand the goals of ethnographic activities and may not translate all of the useful information a design team is trying to collect.

Because a lack of understanding of context was a theme in this research, finding new ways to help engineers overcome that lack of understanding would be valuable to the research commu-

nity. While traveling to a community and being immersed in the context is preferable, it can be cost-prohibitive. There may be other, more cost-effective methods for exposing engineers to new contexts. This could include using inexpensive virtual reality tools such as Google Cardboard to immerse designers in the community and context before they begin a design project. It would be extremely valuable to have a library of communities and contexts that other engineers could access through virtual reality. This would not provide interaction with members of the community but may be an effective first step in developing the designer's empathy and understanding of the context.

Some areas with the most work related to them found in the literature are cookstoves and charcoal production [175]–[185], food processing [186]–[189], medical products and telemedicine [110], [163], [190]–[202], manufacturing systems [203]–[206], lighting [97], [207]–[211], electrification [120], [212]–[237], and mobile phones and Information and Communication Technology (ICT) [136], [238]–[244]. Products for women are notably lacking in the literature. This could be caused by the fact that the majority of engineers in developed countries are men and/or the fact that topics related to women's needs can be uncomfortable or taboo to discuss, particularly in more traditional developing contexts. One of the principles in Chapter 2 is that women and children are more affected by poverty alleviation efforts than men. Women also face many challenges that men do not, the most obvious of which is bearing children. Products related to feminine hygiene, preventing sexual violence, birth control, safe pregnancy and delivery, breastfeeding, or the care of children would improve or save the lives of millions of women in developing communities and yet they are not nearly as common in the literature as, for example, treadle pumps. The need for products developed by empathic design teams may be greatest and most challenging in this product area. This may also be a product area with the greatest potential for impact because there is so much need with so few competitors and because it is widely accepted that the woman of the family has the greatest affect on the family's chances of emerging from poverty. Having a design team that includes female engineers will likely facilitate the development of products for women in developing communities.

Another challenge in design for the developing world is the abundance of student projects. Reports from implementation trips at the end of the product development are common in the literature. These projects provide exceptional educational experiences for engineering students but

student projects have many constraints that prohibit them from having lasting impact. Among these constraints are the semester time-frame students usually have to work in, limited funds for traveling that prevent pre-development ethnographic studies to inform design decisions, a general lack of design experience, and a lack of long-term sustainability for any product that is developed. Another constraint student projects often face is a lack of manufacturing partners. To deal with this, student groups typically design products that individuals in developing communities can manufacture themselves. Martin Fisher points out that “the readers of this journal are not asked to build their own computers, cars or watches; why, then, should we try to train poor people to design and build their own tools?” [38]. Local, small-scale manufacturing may have some benefits, including strengthening the economy by providing employment, but it is unlikely that this will lead to the widespread and significant impact that is so desperately needed in these communities. The work of designing products for resource-poor individuals is significant and must not be left to student groups alone. Student projects expose young engineers to this type of design which is beneficial but the work of designing products that alleviate poverty is far too urgent and significant to leave to the least experienced among us. Professional designers and engineers must also be engaged in this work if we as engineers are to have a significant impact on the lives of those living in extreme poverty.

The work included in this dissertation is a step toward identifying foundational principles and insights for design for the developing world— but it is just one step. Much more effort is required before engineers are able to meet the needs of resource-poor individuals in developing communities as consistently and reliably as we design products that satisfy the needs of customers in the developed world. This chapter outlines several potential paths researchers can pursue to continue to build the foundation for the design of developing world products and there are also many other paths that must be explored. Reducing the number of people living in poverty is a large undertaking. There is a part that only product design engineers can play and principles and insights such as the ones described here will enable us to play that part more effectively.

REFERENCES

- [1] World Bank, “World development indicators,” tech. rep., World Bank, 2010. 1, 14
- [2] W. Bank, “Poverty and shared prosperity 2016: Taking on inequality,” tech. rep., World Bank, 2016. 1
- [3] C. A. Mattson and A. G. Winter, “Why the developing world needs mechanical design,” *Journal of Mechanical Design*, vol. 138, no. 7, p. 070301, 2016. 1, 153
- [4] M. Airhart, “Expandable irrigation systems help poor,” 2008. 1
- [5] S. Subrahmanyam and J. Gomez-Arias, “Integrated approach to understanding consumer behavior at the bottom of the pyramid,” *Journal of Consumer Marketing*, vol. 25, pp. 402–412, 2008. 1, 14, 23, 39, 40, 46, 158
- [6] S. Boztepe, “Toward a framework of product development for global markets: a user-value-based approach,” *Design Studies*, vol. 28, pp. 513–533, 2007. 1, 14
- [7] J. Ramachandran, A. Pant, and S. Pani, “Building the BoP producer ecosystem: the evolving engagement of Fabindia with Indian handloom artisans,” *Journal of Product Innovation Management*, vol. 29, no. 1, pp. 33–51, 2012. 1, 14
- [8] D. Dunn and K. Yamashita, “Microcapitalism and the mega-corporation,” *Harvard Business Review*, vol. 81, no. 8, pp. 46–54, 2003. 1, 14
- [9] R. Guesalaga and P. Marshall, “Purchasing power at the bottom of the pyramid: differences across geographic regions and income tiers,” *Journal of Consumer Marketing*, vol. 25, pp. 413–418, 2008. 1, 14
- [10] A. Kolk and R. van Tulder, “Poverty alleviation as business strategy? Evaluating commitments of frontrunner multinational corporations,” *World Development*, vol. 34, no. 5, pp. 789–801, 2006. 1, 14
- [11] T. Perry, “Doing well by doing good.” *IEEE Spectrum*, January 2007. 1, 14
- [12] C. Prahalad and A. Hammond, “Serving the world’s poor, profitably,” *Harvard Business Review*, vol. R0209C, pp. 4–11, 2002. 1, 14
- [13] A. Rao, “Financing innovations for the bottom of the pyramid,” *Social Science Research*, 2007. 1, 14
- [14] E. Simanis and S. Hart, “Expanding possibilities at the base of the pyramid,” *Innovations: Technology, Governance, Globalization*, vol. 1, no. 1, pp. 43–51, 2006. 1, 14

- [15] World Bank, “The next 4 billion: market size and business strategy at the base of the pyramid,” tech. rep., World Bank, 2007. 1, 14
- [16] P. Werhane, L. Hartman, and S. Kelley, “Saint Vincent de Paul and the mission of the Institute for Business and Professional Ethics: why companies should care about poverty,” *Vincentian Heritage Journal*, vol. 28, no. 2, pp. 141–150, 2008. 1, 14
- [17] V. Margolin, “Design for development: towards a history,” *Design Studies*, vol. 28, pp. 111–115, 2007. 1, 15, 36, 38, 46
- [18] Engineers Without Borders USA, “Charting EWB-USA’s impact,” 2012. 1, 15
- [19] J. Falcioni, “Research in extreme affordability,” *Journal of Mechanical Engineering*, vol. 133, no. 5, 2011. 1, 15
- [20] M. Dornan, “Solar-based rural electrification policy design: the Renewable Energy Service Company (RESCO) model in Fiji,” *Renewable Energy*, vol. 36, no. 2, pp. 797–803, 2011. 1, 15
- [21] M. Jenkins, “Water and sanitation human rights for stone quarry communities in Wagholi, India,” *Journal of Humanitarian Engineering*, vol. 1, pp. 1–6, 1 2011. 1, 15
- [22] W. Biswas, P. Bryce, and M. Diesendorf, “Model for empowering rural poor through renewable energy technologies in Bangladesh,” *Environmental Science and Policy*, vol. 4, pp. 333–344, 2001. 1, 2, 15, 26, 28, 38, 46
- [23] E. Ramudu, “Ocean wave energy-driven desalination systems for off-grid coastal communities in developing countries,” in *IEEE Global Humanitarian Technology Conference*, 2011. 1, 15
- [24] M. Hoque, “Design and analysis of a mini solar grid in remote area of Bangladesh,” in *North American Power Symposium*, 2009. 1, 15
- [25] E. Moe and A. Moe, “Off-grid power for small communities with renewable energy sources in rural Guatemalan villages,” in *Global Humanitarian Technology Conference*, 2011. 1, 15
- [26] F. Brikke and M. Bredero, “Linking technology choice with operation and maintenance in the context of community water supply and sanitation,” tech. rep., World Health Organization and IRC Water and Sanitation Centre, 2003. 1, 15
- [27] S. Mok, “New village gadgets: synergy of human-powered generation and ultra-efficient electrical appliances for poverty eradication,” in *Global Humanitarian Technology Conference*, 2011. 1, 15
- [28] C. Wood, P. Lewis, and C. Mattson, “Modular product optimization to alleviate poverty: an irrigation pump case study,” in *ASME Design Engineering Technical Conference DETC2012-71171*, 2012. 1, 15
- [29] J. Morrise, P. Lewis, C. Mattson, and S. Magleby, “A method for designing collaborative products with application to poverty alleviation,” in *ASME Design Engineering Technical Conference DETC2011-47409*, 2011. 1, 15

- [30] A. Winter, M. Bollini, D. DeLatte, B. Judge, H. O’Hanley, J. Pearlman, and N. Scolnik, “The design, fabrication, and performance of the East African Trial Leveraged Freedom Chair,” in *ASME Design Engineering Technical Conference DETC2010-29096*, 2010. 1, 15
- [31] A. Winter, M. Bollini, B. Judge, N. Scolnik, H. O’Hanley, D. Dorsch, S. Mukherjee, and D. Frey, “Stakeholder-driven design evolution of the leveraged freedom chair developing world wheelchair,” in *ASME International Mechanical Engineering Congress and Exposition IMECE2012-88881*, 2012. 1, 15
- [32] S. Sterling and J. Bennett, “Crossing the real chasm in technical development work,” in *IEEE Global Humanitarian Technology Conference*, 2011. 2, 31, 46
- [33] D. Nieuwsma, “Alternative design scholarship: working toward appropriate design,” *Design Issues*, vol. 20, pp. 13–24, 2004. 2, 23, 46, 160
- [34] A. Akubue, “Appropriate technology for socioeconomic development in third world countries,” *Journal of Technology Studies*, vol. 26, no. 1, 2000. 2, 24, 35, 38, 46
- [35] E. Schumacher, *Small is beautiful: economics as if people mattered*. Harper & Row, 1973. 2, 38, 46
- [36] V. Papanek, *Design for human scale*. Van Nostrand Reinhold Company, 1983. 2, 38, 46
- [37] V. Papanek, *Design for the real world: human ecology and social change*. Academy Chicago, 1984. 2, 38, 46
- [38] M. Fisher, “Income as development: KickStart’s pumps help Kenyan farmers transition to a cash economy,” *Innovations: Technology, Governance, Globalization*, vol. 1, pp. 9–30, 2006. 2, 14, 15, 26, 33, 36, 38, 39, 46, 72, 165
- [39] P. Polak, *Out of poverty: what works when traditional approaches fail*. Berrett-Koehler Publishers, 2009. 2, 38, 46
- [40] P. Lewis, C. Mattson, and V. Murray, “An engineering design strategy for reconfigurable products that support poverty alleviation,” in *ASME Design Engineering Technical Conferences DETC2010-28739*, 2010. 2, 15, 26, 38
- [41] J. F. Pease, J. H. Dean, and D. L. Van Bossuyt, “Toward a market-based lean startup product design method for the developing world,” in *ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, American Society of Mechanical Engineers, 2014. 3, 69
- [42] C. A. Mattson and A. E. Wood, “Nine principles for design for the developing world as derived from the engineering literature,” *Journal of Mechanical Design*, vol. 136, no. 12, p. 121403, 2014. 4, 5, 50, 54, 81, 141, 147, 150, 152
- [43] A. E. Wood and C. A. Mattson, “Design for the developing world: Common pitfalls and how to avoid them,” *Journal of Mechanical Design*, vol. 138, no. 3, p. 031101, 2016. 4, 5, 80, 83, 97, 151, 152, 153

- [44] P. M. Troxell and C. Kim, "A method for classifying products designed for the developing world," in *ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pp. V02AT03A057–V02AT03A057, American Society of Mechanical Engineers, 2016. 4
- [45] C. A. Mattson, A. E. Wood, and J. Renouard, "Village Drill: A case study in engineering for global development with five years of data post market-introduction," *Journal of Mechanical Design*, vol. Accepted Manuscript, 2017. 5, 151, 152
- [46] A. E. Wood and C. A. Mattson, "An experiment in cross-border design ethnography in the developing world," *Research in Engineering Design*, vol. Under Review, 2017. 5, 152
- [47] K. Otto and K. Wood, *Product design: techniques in reverse engineering and new product development*. Prentice Hall, 2001. 6, 16, 18, 41, 48, 49, 160
- [48] R. Scupin, "The kj method: A technique for analyzing data derived from japanese ethnology," *Human organization*, vol. 56, no. 2, pp. 233–237, 1997. 6, 8, 52
- [49] Engineers Without Borders Canada, "EWB 2008 Failure Report," tech. rep., Engineers Without Borders Canada, 2008. 8, 22, 46, 51
- [50] A. Osterwalder and Y. Pigneur, *Business model generation: a handbook for visionaries, game changers, and challengers*. John Wiley & Sons, 2013. 9, 51, 53, 66, 78
- [51] K. S. Thacker, K. M. Barger, and C. A. Mattson, "Balancing technical and user objectives in the redesign of a peruvian cookstove," *Development Engineering*, vol. 2, pp. 12–19, 2017. 9
- [52] S. Prabhala, D. Loi, and S. Ganapathy, "Ethnography, ethnography or ethnography? what happens when the same word means different things to different people?," in *Design, User Experience, and Usability. Theory, Methods, Tools and Practice*, pp. 102–110, Springer, 2011. 10, 108
- [53] A. Bowling and S. Ebrahim, *Handbook of Health Research: Investigation, Measurement and Analysis*. McGraw-Hill International, 2005. 11, 108
- [54] R. M. Emerson, R. I. Fretz, and L. L. Shaw, *Writing ethnographic fieldnotes*. University of Chicago Press, 2011. 11, 108, 114, 115
- [55] T. Salvador, G. Bell, and K. Anderson, "Design ethnography," *Design Management Journal (Former Series)*, vol. 10, no. 4, pp. 35–41, 1999. 11, 109
- [56] A. Sarvestani and K. Sienko, "Design ethnography as an engineering tool," *Demand: ASME Global Development Review*, vol. 2, pp. 2–7, 2014. 11, 109, 110
- [57] D. Fetterman, *Ethnography: step-by-step*. SAGE, 2010. 11, 53, 109, 114
- [58] J. Hughes, J. O'Brien, T. Rodden, M. Rouncefield, and I. Sommerville, "Presenting ethnography in the requirements process," in *Requirements Engineering, 1995., Proceedings of the Second IEEE International Symposium on*, pp. 27–34, IEEE, 1995. 11, 109

- [59] J. Chipchase and S. Steinhardt, *Hidden in Plain Sight: How to Create Extraordinary Products for Tomorrow's Customers*. Harper Collins, 2013. 11, 109
- [60] M. G. Green, J. S. Linsey, C. C. Seepersad, K. L. Wood, and D. J. Jensen, "Frontier design: a product usage context method," in *ASME 2006 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pp. 99–113, American Society of Mechanical Engineers, 2006. 11, 71, 109
- [61] *Human Centered Design Toolkit*. IDEO.org, 2011. 11, 69, 109, 114, 138, 160
- [62] *The Field Guide to Human-Centered Design*. IDEO.org, 2015. 11, 109, 114
- [63] J. D. Allen, C. A. Mattson, K. S. Thacker, and S. M. Ferguson, "Design for excess capability to handle uncertain product requirements in a developing world setting," *Research in Engineering Design*, 2017, In Press. 11, 109
- [64] C.-H. Chen, L. P. Khoo, and W. Yan, "Evaluation of multicultural factors from elicited customer requirements for new product development," *Research in Engineering Design*, vol. 14, no. 3, pp. 119–130, 2003. 11, 109
- [65] C. George and A. Shams, "The challenge of including customer satisfaction into the assessment criteria of overseas service-learning projects," *International Journal for Service Learning in Engineering: Humanitarian Engineering and Social Entrepreneurship*, vol. 2, no. 2, pp. 64–75, 2007. 13, 15, 19, 21, 22, 30, 33, 46, 160
- [66] C. Sethi, "Engineering salaries on the rise," July 2012. 14
- [67] A. Gadgil, "Drinking water in developing countries," *Annual Review of Energy and the Environment*, vol. 23, no. 1, pp. 253–286, 1998. 14
- [68] J. Baumgartner, S. Murcott, and M. Ezzati, "Reconsidering 'appropriate technology': the effects of operating conditions on the bacterial removal performance of two household drinking-water filter systems," *Environmental Research Letters*, vol. 2, no. 2, pp. 1–6, 2007. 14, 15
- [69] E. Breslin, "Rethinking hydrophilanthropy: smart money for transformative impact," tech. rep., Water for People, 2010. 14
- [70] R. Carter and K. Danert, "The private sector and water and sanitation services – policy and poverty issues," *Journal of International Development*, vol. 15, no. 8, pp. 1067–1072, 2003. 14, 32
- [71] K. Hamza, M. Shalaby, A. Nassef, M. Aly, and K. Saitou, "Studies on the design of reverse osmosis water desalination systems for cost and energy efficiency," in *ASME Design Engineering Technical Conference DETC2010-28493*, 2010. 14, 15
- [72] M. Kumar, "Arsenic removal for ceramic water filters," *Journal of Humanitarian Engineering*, vol. 1, no. 1, pp. 11–14, 2011. 14, 114
- [73] C. Matlack, H. Chizeck, T. Davis, and J. Linnes, "A low-cost solar disinfection indicator for safe water," in *Global Humanitarian Technology Conference*, 2011. 14

- [74] M. Sobsey, “Managing water in the home: accelerated health gains from improved water supply,” tech. rep., World Health Organization, 2002. 14
- [75] O. Varis, “Right to water: the millennium development goals and water in the MENA region,” *Water Resources Development*, vol. 23, no. 2, pp. 243–266, 2007. 14
- [76] G. White and A. White, “Potable water for all: the Egyptian experience with rural water supply,” tech. rep., Water International, 1986. 14
- [77] S. Postel, P. Polak, F. Gonzales, and J. Keller, “Drip irrigation for small farmers,” *Water International*, vol. 26, pp. 3–13, 2001. 14, 26, 28, 33, 34, 39, 46, 71
- [78] M. Kay and T. Brabben, “Treadle pumps for irrigation in Africa,” tech. rep., Food and Agriculture Organization of the United Nations, 2000. 14
- [79] D. Alder, K. Mgalula, D. Price, and O. Taylor, “Introduction of a portable ultrasound unit into the health services of the Lugufu refugee camp, Kigoma District, Tanzania,” *Emergency Medicine*, vol. 1, pp. 261–266, 2008. 14, 22, 24, 33, 46
- [80] B. Maxted, “Dust masks for Indian quarry workers: a comparative analysis of the filtering efficiency of fabrics,” *Journal of Humanitarian Engineering*, vol. 1, no. 1, pp. 15–20, 2011. 14
- [81] D. Zurovcik, A. Slocum, G. Mody, R. Riviello, and R. Sheridan, “Development of simplified negative pressure wound therapy device for low-resource settings,” *IEEE Global Humanitarian Technology Conference*, 2011. 14
- [82] A. Daar, H. Thorsteinsdottir, D. Martin, A. Smith, S. Nast, and P. Singer, “Top ten biotechnologies for improving health in developing countries,” *Ethics of Science and Technology: Exploration of the Frontiers of Science and Ethics*, pp. 145–158, 2006. 14
- [83] T. Knight and L. Sass, “Looks count: computing and constructing visually expressive mass customized housing,” *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, vol. 24, pp. 425–445, 2010. 14
- [84] M. Gustavsson, “Education benefits from solar technology— access to solar electric services and changes in children’s study routines, experiences from Eastern Province Zambia,” *Energy Policy*, vol. 35, no. 2, pp. 1292–1299, 2007. 14, 24, 46
- [85] Z. Christiansen, D. Homer, and D. Nielson, “Dodging adverse selection: how donor type and governance condition aid’s effects on school enrollment,” *World Development*, vol. 39, no. 11, pp. 2044–2053, 2011. 14, 32
- [86] A. Gordon, “Facilitating education in rural areas of South Africa,” tech. rep., University of Cape Town Energy and Development Research Centre, 1997. 14
- [87] S. Chaplin, “Social exclusion and the politics of sanitation in urban India,” *Environment and Urbanization*, vol. 11, no. 1, pp. 145–158, 1999. 14
- [88] A. Lopes, D. Fam, and J. Williams, “Designing sustainable sanitation: involving design in innovative, transdisciplinary research,” *Design Studies*, vol. 33, pp. 298–317, 2012. 14

- [89] S. Burra, S. Patel, and T. Kerr, "Community-designed, built and managed toilets blocks in Indian cities," *Environment and Urbanization*, vol. 15, pp. 11–32, 2003. 14, 18, 19, 22, 26, 28, 35, 46
- [90] UNICEF, "An evaluation of the playpump water system as an appropriate technology for water, sanitation and hygiene programmes," tech. rep., UNICEF, 2007. 14
- [91] N. Wasley, P. Lewis, and C. Mattson, "Designing products for optimal collaborative performance with application to engineering-based poverty alleviation," in *AMSE Design Engineering Technical Conference DETC2012-71209*, 2012. 15
- [92] J. Austin-Breneman and M. Yang, "Design for micro-enterprise: an approach to product design for emerging markets," in *ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, American Society of Mechanical Engineers, 2013. 15, 71, 81
- [93] S. Murcott, "Co-evolutionary design for development: influences shaping engineering design and implementation in Nepal and the global village," *Journal of International Development*, vol. 19, no. 1, pp. 123–144, 2007. 15, 18, 21, 28, 46
- [94] R. Campbell, P. Lewis, and C. Mattson, "A method for identifying design principles for the developing world," in *ASME Design Engineering Technical Conference DETC2011-48584*, 2011. 15, 43, 49
- [95] A. Andersen and C. Kim, "Principles of mechanical design for the developing world: a case study approach," in *ASME Design Engineering Technical Conference DETC2011-48245*, 2011. 15
- [96] K. Bryden, "Understanding rural village energy needs and design constraints," in *ASME Design Engineering Technical Conference DETC2011-48669*, 2011. 15, 19, 26, 46
- [97] B. Sloan, "A case study of the implementation and maintenance of a fee for service lighting system for a rural village in Sub-Saharan Africa," in *ASME Design Engineering Technical Conference DETC2012-71469*, 2012. 15, 47, 164
- [98] B. Hazeltine and C. Bull, *Field Guide to Appropriate Technology*. Academic Press, 2003. 15
- [99] S. Arif and Z. Siddique, "Design and selection of safe water supply solutions for emerging regions - a demography based demand driven approach," in *AMSE International Design Engineering Technical Conference*, 2012. 15
- [100] D. Nieuwsma and D. Riley, "Designs on development: engineering, globalization and social justice," *Journal of the International Network for Engineering Studies*, vol. 2, pp. 29–59, 2010. 18, 19, 23, 30, 33, 46
- [101] J. Linsey, A. Markman, and K. Wood, "Design by analogy: a study of the WordTree Method for problem re-representation," *Journal of Mechanical Design*, vol. 134, no. 4, 2012. 18

- [102] S. Takai, V. Jikar, and K. Ragsdell, “An approach toward integrating top-down and bottom-up concept and design selection,” *Journal of Mechanical Design*, vol. 133, no. 7, 2011. 18
- [103] D. Ullman, *The mechanical design process*. McGraw Hill, 2010. 18, 41, 43, 44, 45, 46, 48, 49
- [104] G. Pahl and W. Beitz, *Engineering design: a systematic approach*. Springer Science & Business Media, 2013. 18, 25, 41, 46, 48, 49, 87, 160
- [105] N. Sawhney, *Open collaborative design: understanding the role of online tools and social incentives towards sustainable design and learning*. PhD thesis, Massachusetts Institute of Technology, 2002. 18, 46
- [106] H. Cruickshank and R. Fenner, “The evolving role of engineers: toward sustainable development of the built environment,” *Journal of International Development*, vol. 19, pp. 111–121, 2007. 19, 26, 33, 46
- [107] J. Novy-Hildesley, “From idea to impact: funding intervention for sustainability,” *Innovations: Technology, Governance, Globalization*, vol. 1, no. 1, pp. 31–42, 2006. 19, 33, 39, 40, 46
- [108] T. Witherspoon and E. Harris, “Avoiding the 30-pound paperweight: success via contextually appropriate technologies,” in *IEEE Global Humanitarian Technology Conference*, 2011. 19, 24, 46, 160
- [109] W. Brunette, W. Gerard, M. Hicks, A. Hope, M. Ishimitsu, P. Prasad, R. Anderson, G. Borriello, B. Kolko, and R. Nathan, “Portable antenatal ultrasound platform for village midwives,” *Annual Symposium on Computing for Development*, 2010. 19, 46
- [110] D. Ramachandran, J. Cranny, P. Das, and E. Cutrell, “Mobile-izing health workers in rural India,” in *International Conference on Human Factors in Computing Systems*, 2010. 19, 26, 46, 47, 164
- [111] G. Bixler, “Extreme user centered design: methodology for eliciting and ranking requirements in user-centered new product development: case studies from Honduras and the Central African Republic,” in *IEEE Global Humanitarian Technology Conference*, 2011. 19, 46
- [112] P. Braund and A. Schwittay, “The missing piece: human-driven design and research in ICT and development,” in *IEEE International Conference on ICT and Development*, 2006. 19, 46
- [113] D. Ramachandran, M. Kam, J. Chiu, J. Canny, and J. Frankel, “Social dynamics of early stage co-design in developing regions,” in *SIGCHI Conference on Human Factors in Computing Systems*, 2007. 19, 46
- [114] A. Rao, “Rising creative class in India,” *Social Science Research*, 2007. 19, 46

- [115] J. Lai, T. Honda, and M. Yang, “A study of the role of user-centered design methods in design team projects,” *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, vol. 24, pp. 303–316, 2010. 19, 46
- [116] B. Martin and B. Hanington, *Universal methods of design: 100 ways to research complex problems, develop innovative ideas, and design effective solutions*. Rockport Publishers, 2012. 20, 114
- [117] R. Bailis, V. Berrueta, C. Chengappa, K. Dutta, R. Edwards, O. Masera, D. Still, and K. Smith, “Performance testing for monitoring improved biomass stove interventions: experiences of the household energy and health project,” *Energy for Sustainable Development*, vol. 11, pp. 57–70, 2007. 21, 22, 46
- [118] K. Scott, “Developing a manual to guide project evaluation for RainWater Cambodia,” *Journal of Humanitarian Engineering*, vol. 1, pp. 7–10, 2011. 21, 46
- [119] R. D. Harris and W. M. Marks, “Compact ultrasound for improving maternal and perinatal care in low-resource settings: Review of the potential benefits, implementation challenges, and public health issues,” *Journal of Ultrasound in Medicine*, vol. 28, no. 8, pp. 1067–1076, 2009. 21, 23, 29, 36, 46
- [120] V. Natarajan, A. Baxi, R. Padmanabhan, and V. Mageshkumar, “Low cost bio-mechanical energy generator for off-grid users,” in *IEEE Global Humanitarian Technology Conference*, 2011. 22, 46, 47, 164
- [121] C. George, D. Elton, H. Garwick, and G. Ewing, “How understanding local challenges and opportunities influenced the design of post-harvesting technology in Haiti,” in *Open Catalyzing Innovation*, 2011. 22, 33, 46
- [122] H. Louie, “Design and testing of a small human-powered generator for developing rural communities,” in *North American Power Symposium*, 2010. 22, 24, 46
- [123] D. Jue, “Improving the long-term sustainability of service-learning projects: six lessons learned from early MIT IDEAS competition winners,” *International Journal for Service Learning in Engineering: Humanitarian Engineering and Social Entrepreneurship*, vol. 6, no. 2, pp. 19–29, 2011. 22, 46
- [124] Engineers Without Borders Canada, “EWB 2009 Failure Report,” tech. rep., Engineers Without Borders Canada, 2009. 22, 46, 51
- [125] Engineers Without Borders Canada, “EWB 2010 Failure Report,” tech. rep., Engineers Without Borders Canada, 2010. 22, 46, 51
- [126] Engineers Without Borders Canada, “EWB 2011 Failure Report,” tech. rep., Engineers Without Borders Canada, 2011. 22, 46, 51
- [127] Engineers Without Borders Canada, “EWB 2012 Failure Report,” tech. rep., Engineers Without Borders Canada, 2012. 22, 46, 51

- [128] T. Ngai, R. Shrestha, B. Dangol, M. Maharjan, and S. Murcott, "Design for sustainable development- household drinking water filter for arsenic and pathogen treatment in Nepal," *Journal of Environmental Science and Health, Part A: Toxic/Hazardous Substances and Environmental Engineering*, vol. 42, no. 12, pp. 1879–1888, 2007. 22, 46
- [129] K. Donaldson, "Product design in less industrialized economies: constraints and opportunities in Kenya," *Research in Engineering Design*, vol. 17, pp. 135–155, 2006. 23, 46
- [130] J. Weiss, C. George, and J. Walker, "Redesigning an appropriate technology shredder for manufacture in a developing country," *International Journal for Service Learning in Engineering: Humanitarian Engineering and Social Entrepreneurship*, vol. 1, no. 1, pp. 11–26, 2006. 23, 46
- [131] P. Wijayatunga and R. Attalage, "Analysis of rural household energy supplies in Sri Lanka: energy efficiency, fuel switching and barriers to expansion," *Energy Conversion & Management*, vol. 44, no. 7, pp. 1123–1130, 2003. 24, 25, 46
- [132] C. White, L. Bank, S. Jones, and M. Mehlwana, "Restricted electricity use among poor urban households," *Development Bank of South Africa*, vol. 14, no. 3, pp. 413–423, 1997. 24, 46
- [133] L. Downey, "For people without power: solving energy problems in a new way," in *Global Humanitarian Technology Conference*, 2011. 24, 46
- [134] L. Lazaroff, "Grandiose plans for a wired planet yield to pragmatic aims," *Choices: The Human Development Magazine*, vol. December, pp. 7–9, 2003. 25
- [135] A. Parkinson, C. Sorensen, and N. Pourhassan, "A general approach for robust optimal design," *Journal of Mechanical Design*, vol. 115, no. 1, 1993. 25
- [136] K. Roux and M. Marais, "Design for sustainability: rural connectivity with village operators," in *IEEE Global Humanitarian Technology Conference*, 2011. 26, 47, 164
- [137] UN Habitat, "Slum dwellers to double by 2030: millennium development goals could fall short," tech. rep., UN Habitat, 2007. 26, 46
- [138] O. Morawczynski and G. Miscione, "Examining trust in mobile banking transactions: the case of M-PESA in Kenya," in *Proceedings of the Eighth International Conference on Human Choice and Computers*, 2008. 26, 46
- [139] C. George, A. Shams, and F. Dunkel, "Lessons learned in an international service-learning collaborative: shea butter case study," *North American Colleges and Teachers of Agriculture (NACTA) Journal*, vol. 13, pp. 71–77, 2011. 30, 31, 46
- [140] J. Blizzard and L. Klotz, "A framework for sustainable whole systems design," *Design Studies*, vol. 33, pp. 456–479, 2012. 31, 46
- [141] M. Viswanathan, A. Yassine, and J. Clarke, "Sustainable product and market development for subsistence marketplaces: creating educational initiatives in radically different contexts," *Journal of Product Innovation Management*, vol. 28, pp. 558–569, 2011. 31, 46

- [142] A. Banzaert, “Experiments in service learning,” tech. rep., Massachusetts Institute of Technology, 2006. 31, 46
- [143] J. Smith, L. Brown, L. B. D. Loden, and J. O’Shea, “New partnerships linking universities and NGO’s on education for development engineering- a case study from Engineers Without Borders Australia,” in *Joint International IGIP-SEFI Annual Conference*, 2010. 31, 46
- [144] W. Oakes, J. Duffy, T. Jacobius, P. Linos, S. Lord, W. Schultz, and A. Smith, “Service-learning in engineering,” in *Frontiers in Education Conference*, 2002. 31, 46
- [145] J. O’Shea and C. Baillie, “Engineering education towards social and environmental justice,” in *Proceedings of the 2011 AAEE Conference*, 2011. 31, 46
- [146] E. Thomas, Z. Zumar, C. Barstow, and K. Linden, “Proving sustainability: the international development monitoring initiative,” in *IEEE Global Humanitarian Technology Conference*, 2011. 31, 46
- [147] A. Andersen, “A method for assessing the sustainability of design in developing world projects,” Master’s thesis, Bucknell University, 2012. 31, 46
- [148] G. Evans, “The environment of childhood poverty,” *American Psychologist*, vol. 59, no. 2, p. 77, 2004. 32
- [149] M. Adato, M. Carter, and J. May, “Exploring poverty traps and social exclusion in South Africa using qualitative and quantitative data,” *Journal of Development Studies*, vol. 42, no. 2, pp. 226–247, 2006. 32
- [150] K. Curtis, “Urban poverty and the social consequences of privatized food assistance,” *Journal of Urban Affairs*, vol. 19, no. 2, pp. 207–226, 1997. 32
- [151] A. Goetz and D. O’Brien, “Governing for the common wealth? The World Bank’s approach to poverty and governance,” *Institute of Developmental Studies Bulletin*, vol. 26, no. 2, pp. 17–26, 1995. 32
- [152] Y. Sawada, “Dynamic poverty problem and the role of infrastructure,” *Japan Bank for International Cooperation Review*, pp. 20–40, 2000. 32
- [153] D. Singleton, “Poverty alleviation: the role of the engineer,” *Arup Journal*, vol. 38, no. 1, pp. 3–9, 2003. 32, 33, 46
- [154] N. Dasgupta, “Environmental enforcement and small industries in India: reworking the problem in the poverty context,” *World Development*, vol. 28, no. 5, pp. 945–967, 2000. 32
- [155] W. Rees, “Ecological footprints and appropriated carrying capacity: what urban economics leaves out,” *Environment and Urbanization*, vol. 4, no. 2, pp. 121–130, 1992. 32
- [156] B. Baulch and J. Hoddinott, “Economic mobility and poverty dynamics in developing countries,” *Journal of Development Studies*, vol. 36, no. 6, pp. 1–24, 2000. 32
- [157] G. Datt, “Has poverty declined since economic reforms? Statistical data analysis,” *Economic and Political Weekly*, pp. 3516–3518, 1999. 32

- [158] A. Banerjee and E. Duflo, *Poor economics: a radical rethinking of the way to fight global poverty*. Public Affairs, 2011. 32
- [159] J. Morduch, “The microfinance promise,” *Journal of Economic Literature*, vol. 37, no. 4, pp. 1569–1614, 1999. 32
- [160] T. Brown, *Change by design*. HarperCollins, 2009. 32
- [161] T. Addison, D. Hulme, and R. Kanbur, *Poverty dynamics: interdisciplinary perspectives*. Oxford University Press, 2009. 33, 46
- [162] J. Sachs, *The end of poverty: economic possibilities of our time*. Penguin Group, 2006. 33, 46
- [163] M. Murillo and D. Wright, “Experiences in volunteer dynamics, inter-organizational collaboration and leadership for the purpose of deploying telemedicine solutions in remote areas in developing nations,” in *IEEE Global Humanitarian Technology Conference*, 2011. 33, 46, 47, 164
- [164] T. Pinch and W. Bijker, “The social construction of facts and artifacts: or how the sociology of science and the sociology of technology might benefit each other,” *Social Studies of Science*, vol. 14, no. 3, pp. 399–441, 1984. 33, 46
- [165] E. Schoolman, J. Guest, K. Bush, and A. Bell, “How interdisciplinary is sustainability research? Analyzing the structure of an emerging scientific field,” *Sustainability Science*, vol. 7, no. 1, pp. 67–80, 2012. 33, 46
- [166] W. Fulkerson, M. Levine, J. Sinton, and A. Gadgil, “Sustainable, efficient electricity service for one billion people,” *Energy for Sustainable Development*, vol. 6, no. 2, pp. 26–34, 2005. 35, 46
- [167] C. Uko, “Engineering research - are developing nations getting value for money?,” *Journal of Professional Issues in Engineering*, vol. 113, no. 3, pp. 236–240, 1987. 36, 46
- [168] B. Singley, “Computer-based instruction for engineering education in the developing world,” Master’s thesis, Brigham Young University, 2007. 36, 46
- [169] A. Pamuk and P. Cavallieri, “Alleviating urban poverty in a global city: new trends in upgrading Rio-de-Janeiro’s Favelas,” *Habitat International*, vol. 22, no. 4, pp. 449–462, 1998. 36, 46
- [170] K. Darrow and M. Saxenian, *Appropriate technology sourcebook: a guide to practical books for village and small community technology*. Volunteers in Asia, 1986. 38, 46
- [171] C. Nakata and K. Weidner, “Enhancing new product adoption at the base of the pyramid: a contextualized model,” *Journal of Product Innovation Management*, vol. 29, pp. 21–23, 2012. 39, 46
- [172] A. Maslow, “A theory of human motivation,” *Psychological Review*, vol. 50, no. 4, pp. 370–396, 1943. 40

- [173] J. Yum, "The impact of Confucianism on interpersonal relationships and communication patterns in east Asia," *Communication Monographs*, vol. 55, no. 4, pp. 374–388, 1988. 40
- [174] S. Pugh, *Total Design: Integrated Methods for Successful Product Engineering*. Prentice Hall, 1991. 41, 44, 46, 48, 49
- [175] N. MacCarty, D. Still, and D. Ogle, "Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance," *Energy for Sustainable Development*, vol. 14, no. 3, pp. 161–171, 2010. 47, 164
- [176] A. Mazzu, "Study, design and prototyping of an animal traction cam based press for biomass densification," *Journal of Mechanism and Machine Theory*, vol. 42, pp. 652–667, 2007. 47, 164
- [177] C. Roden, T. Bond, S. Conway, A. Pinel, N. MacCarty, and D. Still, "Laboratory and field investigations of particulate and carbon monoxide emissions from traditional and improved cookstoves," *Atmospheric Environment*, vol. 43, no. 6, pp. 1170–1181, 2009. 47, 164
- [178] V. Berrueta, R. Edwards, and O. Masera, "Energy performance of woodburning cookstoves in Michoacan, Mexico," *Renewable Energy*, vol. 33, no. 5, pp. 859–870, 2008. 47, 164
- [179] World Bank, "Household cookstoves, environment, health, and climate change: a new look at an old problem," tech. rep., World Bank, 2011. 47, 164
- [180] A. Smith and S. Frayne, "Fuel from the fields: A case study of sugarcane charcoal technology in Petite Anse, Haiti," tech. rep., Massachusetts Institute of Technology, 2004. 47, 164
- [181] B. Limmeechokchai and S. Chawana, "Sustainable energy development strategies in the rural Thailand: the case of the improved cooking stove and the small biogas digester," *Renewable & Sustainable Energy Reviews*, vol. 11, pp. 818–837, 2007. 47, 164
- [182] N. Johnson, A. Hallam, M. Bryden, and S. Conway, "Sustainable and market-based analysis of cooking technologies in developing countries," in *ASME International Mechanical Engineering Congress and Exposition IMECE2006-15375*, 2006. 47, 164
- [183] V. Fan, "Design of a crushing and agglomeration process for manufacturing bagasse charcoal," tech. rep., Massachusetts Institute of Technology, 2006. 47, 164
- [184] R. Caro, H. de Frutos, A. Kitwana, and A. Shen, "Typha charcoal in Senegal: changing a national threat into durable wealth," tech. rep., Massachusetts Institute of Technology, 2011. 47, 164
- [185] E. Toussaint, "Converting sugarcane waste into charcoal for Haiti," tech. rep., Massachusetts Institute of Technology, 2007. 47, 164
- [186] D. Lee, "Peanut oil press redesign for developing countries," tech. rep., Massachusetts Institute of Technology, 2007. 47, 164
- [187] R. Patel, "Maximum of oil output of a treadle-powered peanut oil press," tech. rep., Massachusetts Institute of Technology, 2007. 47, 164

- [188] R. Ramli, “Designing and building peanut-shelling machine to help people in third world countries such as Ghana/Haiti,” tech. rep., Massachusetts Institute of Technology, 2004. 47, 164
- [189] A. Sabelli, “Design of a press for oil extraction from moringa seeds for Haiti,” tech. rep., Massachusetts Institute of Technology, 2004. 47, 164
- [190] C. Causer, “Changing the world: handheld diagnostic lab scores top priority,” *IEEE Potentials*, 2009. 47, 164
- [191] S. Jones, “Sure chill refrigeration technology: improving the cold chain in the developing world,” *IEEE Global Humanitarian Technology Conference*, 2011. 47, 164
- [192] K. Sienko, A. Sarvestani, and L. Grafman, “Medical device compendium for the developing world: a new approach in project and service-based learning for engineering graduate students,” *Global Journal of Engineering Education*, vol. 15, no. 1, 2013. 47, 164
- [193] J. Perosky, R. Rabban, J. Bradshaw, A. Gienapp, A. Ofosu, and K. Sienko, “Designing a portable gynecological examination table: improving access to antenatal care in rural Ghana,” *International Journal for Service Learning in Engineering: Humanitarian Engineering and Social Entrepreneurship*, vol. 7, no. 1, 2012. 47, 164
- [194] C. Sung, R. Karmath, Y. Cui, C. Ouyang, E. Carstens, D. Ramos, and Z. Oden, “Design of a novel mechanical syringe pump for neonatal care in low-resource settings,” *IEEE Global Humanitarian Technology Conference*, 2011. 47, 164
- [195] P. Lokuge, Y. Maguire, and A. Wu, “Design of a passive incubator for premature infants in the developing world,” tech. rep., Massachusetts Institute of Technology, 2002. 47, 164
- [196] W. Richard, D. Zar, and R. Solek, “A low-cost b-mode USB ultrasound probe,” *Ultrasonic Imaging*, vol. 1, no. 5, pp. 21–28, 2009. 47, 164
- [197] S. Khoja and A. Naseem, “E-health in international networks: new opportunities for collaboration,” *TeleHealth in the Developing World*, 2009. 47, 164
- [198] A. Martinez, V. Villarroel, J. Seoane, and F. del Pozo, “A study of a rural telemedicine system in the Amazon region of Peru,” *Telecare*, vol. 10, pp. 219–225, 2004. 47, 164
- [199] M. Pradhan, “Telemedicine in Nepal,” *TeleHealth in the Developing World*, 2009. 47, 164
- [200] N. Thomas, I. Lahdesmaki, A. Lingley, Y. Liao, J. Pandey, A. Afanasiey, B. Otis, T. Shen, and B. Parviz, “Functional contact lenses for remote health monitoring in developing countries,” *IEEE Global Humanitarian Technology Conference*, 2011. 47, 164
- [201] S. Veeraraghaven and S. Vasen, “Information management in resource poor settings for the healthcare sector,” *International Conference on e-Health Networking, Application and Services*, pp. 289–291, 2007. 47, 164
- [202] R. Wooton, N. Patil, R. Scott, and K. Ho, “Telehealth in the developing world,” tech. rep., International Development Research Centre, 2009. 47, 164

- [203] J. Letechipia, A. Arredondo, G. Fregoso, D. Jourdain, and A. Alessi, “Design and development of a system to manually fabricate contoured seats for children with disabilities,” in *IEEE Global Humanitarian Technology Conference*, 2011. 47, 164
- [204] P. Melendez-Vega, G. Venkataramanan, D. Ludois, and J. Reed, “Low-cost light-weight quick-manufacturable blades for human-scale wind turbines,” in *Global Humanitarian Technology Conference*, 2011. 47, 164
- [205] S. Quinlan, “Designing of a prototype heat-sealer to manufacture solar water sterilization pouches for use in developing nations,” tech. rep., Massachusetts Institute of Technology, 2005. 47, 164
- [206] L. Schlecht, “Product development of a device for manufacturing medical equipment for use in low-resource settings,” tech. rep., Massachusetts Institute of Technology, 2010. 47, 164
- [207] F. Nieuwenhout, P. V. de Rijt, and E. Wiggelinkhuizen, “Rural lighting services, a comparison of lamps for domestic lighting in developing countries,” tech. rep., Netherlands Energy Research Foundation, 1998. 47, 164
- [208] B. Schultz, “Development and commercialization of rechargeable wooden LED lamps,” *Journal of Humanitarian Engineering*, vol. 1, no. 1, pp. 21–25, 2011. 47, 164
- [209] N. Watson, T. Scott, and S. Hirsch, “Implications for distribution networks of high generation of compact fluorescent lamps,” *IEEE Transactions on Power Delivery*, vol. 24, pp. 26–34, July 2009. 47, 164
- [210] E. Mills, “Technical and economic performance analysis of kerosene lamps and alternative approaches to illumination in developing countries,” tech. rep., Lawrence Berkeley National Laboratory, 2003. 47, 164
- [211] R. V. D. Plas, “Improving rural lighting in developing countries: call for action among lighting equipment suppliers,” in *European Conference on Energy-Efficient Lighting*, 1997. 47, 164
- [212] F. Giudice and G. L. Rosa, “Design, prototyping and experimental testing of a chiral blade system for hydroelectric microgeneration,” *Journal of Mechanism and Machine Theory*, vol. 44, pp. 1463–1484, 2009. 47, 164
- [213] W. Ratterman, “Solar electricity for the developing world,” *Home Power*, vol. 119, 2007. 47, 164
- [214] J. Reed, G. Venkataramanan, and J. Rose, “Modeling of battery charging wind turbines,” in *International Conference on Power Electronics*, 2007. 47, 164
- [215] J. Susanto, “Limits of grid expansion in the Lao PDR: a financial perspective,” *Journal of Humanitarian Engineering*, vol. 1, pp. 27–38, 2011. 47, 164
- [216] K. Unger and M. Kazerani, “Simulation of rural electrification via cellular-enabled micro-inverter,” in *IEEE Global Humanitarian Technology Conference*, 2011. 47, 164

- [217] E. Youngren, "Shortcut to failure: why whole system integration and balance of system components are crucial to off-grid PV system sustainability," in *Global Humanitarian Technology Conference*, 2011. 47, 164
- [218] H. Piggott, S. Dunnett, and S. Khennas, "Small wind systems for battery charging - a guide for development workers," tech. rep., ITDG, 2001. 47, 164
- [219] R. Podmore and H. Louie, "Affordable energy solutions for developing communities," in *Power and Energy Society General Meeting*, 2011. 47, 164
- [220] D. Miller, *Selling solar: the diffusion of renewable energy in emerging markets*. Earthscan, 2009. 47, 164
- [221] M. Madubansi and C. Shackleton, "Changing energy profiles and consumption patterns following electrification in five rural villages, South Africa," *Energy Policy*, vol. 34, pp. 4081–4092, 2006. 47, 164
- [222] D. Ludois, J. Lee, P. Mendoza, and G. Venkataramanan, "Reuse of post-consumer e-waste for low cost micropower distribution," in *Global Humanitarian Technology Conference*, 2011. 47, 164
- [223] H. Louie, "Electromagnetic field modeling of appropriate technology generators for rural electrification applications," in *IEEE Global Humanitarian Technology Conference*, 2011. 47, 164
- [224] H. Louie, "Experiences in the construction of open source low technology off-the-grid wind turbines," in *IEEE Power and Energy Society General Meeting*, 2011. 47, 164
- [225] K. Kusakana, J. Munda, and A. Jimoh, "Feasibility study of a hybrid PV-micro hydro system for rural electrification," in *AFRICON*, 2009. 47, 164
- [226] M. Gomez and S. Silveira, "Rural electrification of the Brazilian Amazon: achievements and lessons," *Energy Policy*, vol. 38, no. 10, pp. 6251–6260, 2010. 47, 164
- [227] D. Barnes, "Electric power for rural growth: how electricity affects rural life in developing countries," *Rural Sociology*, vol. 54, no. 1, pp. 132–135, 1989. 47, 164
- [228] S. Babu, "Off-grid solar power for remote habitations: lessons in sustainability," in *Global Humanitarian Technology Conference*, 2011. 47, 164
- [229] M. Hankins, *Stand-alone solar electric systems*. Earthscan, 2010. 47, 164
- [230] N. Johnson, *Village energy system dynamics of an isolated West African village*. PhD thesis, Iowa State University, 2012. 47, 164
- [231] W. Floor and R. Masse, "Peri-urban electricity consumers, a forgotten but important group: What can we do to electrify them?," tech. rep., Joint UN Development Programme/World Bank Energy Sector Management Assistance Program, 2001. 47, 164
- [232] C. Haanyika, "Rural electrification in Zambia: a policy and institutional analysis," *Energy Policy*, vol. 36, no. 3, pp. 1044–1058, 2008. 47, 164

- [233] M. Davis, “Rural household energy consumption: the effects of access to electricity– evidence from South Africa,” *Energy Policy*, vol. 26, no. 3, pp. 207–217, 1998. 47, 164
- [234] World Energy Outlook, “Implications of current energy policies,” tech. rep., World Energy Outlook, 2009. 47, 164
- [235] Ministry of Power India, “Technology: enabling the transformation of power distribution, roadmap and reforms,” tech. rep., Ministry of Power India, Centre for Study of Science, Technology and Policy, and Bangalore & Infosys Technologies, 2008. 47, 164
- [236] International Bank for Reconstruction and Development, “The welfare impact of rural electrification: a reassessment of the costs and benefits,” tech. rep., International Bank for Reconstruction and Development, 2008. 47, 164
- [237] World Bank, “The welfare impact of rural electrification: a reassessment of the costs and benefits,” tech. rep., World Bank, 2008. 47, 164
- [238] A. Chircu and V. Mahajan, “Revisiting the digital divide: an analysis of mobile technology depth and service breadth in the BRIC countries,” *Journal of Product Innovation Management*, vol. 26, pp. 455–466, 2009. 47, 164
- [239] S. Wooder and S. Baker, “Extracting key lessons in service innovation,” *Journal of Product Innovation Management*, vol. 29, pp. 13–20, 2012. 47, 164
- [240] A. Bhavnani, R. Chiu, S. Janakiram, and P. Silarszky, “The role of mobile phones in sustainable rural poverty reduction,” tech. rep., ICT Policy Division, Global Information and Communications Department, 2008. 47, 164
- [241] P. Braund, K. Frauscher, A. Schwittay, and D. Petkoski, “Information and communications technology for economic development,” tech. rep., World Bank, 2006. 47, 164
- [242] P. Kaushik and N. Singh, “Information technology and broad-based development: preliminary lessons from North India,” *World Development*, vol. 32, pp. 591–607, 2004. 47, 164
- [243] J. Navas-Sabater, “Telecommunications and information services for the poor,” tech. rep., World Bank Discussion Paper No 432, 2002. 47, 164
- [244] D. Schon, B. Sanyal, and W. Mitchell, *Technology and low-income communities: prospects for the positive use of advanced information technology*. MIT Press, 1999. 47, 164
- [245] Y. Cai, G. Huang, Z. Yang, W. Sun, and B. Chen, “Investigation of public’s perception towards rural sustainable development based on a two-level expert system,” *Expert Systems with Applications*, vol. 36, pp. 8910–8924, 2009. 47
- [246] S. Chen and M. Ravallion, “How have the world’s poorest fared since the early 1980s?” tech. rep., World Bank, 2004. 47
- [247] W. Easterly, *The white man’s burden: why the west’s efforts to aid the rest have done so much ill and so little good*. Penguin Group, 2006. 47

- [248] D. D. Group, “Poverty data: a supplement to world development indicators,” tech. rep., The World Bank, 2008. 47
- [249] G. Ferraro, *The cultural dimension of international business*. Prentice Hall, 1994. 47
- [250] C. Prahalad, *The fortunate at the bottom of the pyramid: eradicating poverty through profits*. FT Press, 2010. 47
- [251] L. Nelson, “Research and development strategies for innovations that alleviate poverty,” *Studies in Material Thinking*, vol. 6, pp. 1–12, 2011. 47
- [252] C. Smith, *Design for the other 90%*. Cooper-Hewitt, National Design Museum, Smithsonian Organization, 2007. 47
- [253] S. Smith, *Ending global poverty: a guide to what works*. Palgrave Macmillan, 2008. 47
- [254] S. Veeraraghaven and P. Krishnaswamy, “A novel technology based framework to address global humanitarian issues,” in *IEEE Global Humanitarian Technology Conference*, 2011. 47
- [255] R. Bijapurkar, “The new, improved Indian consumer.” *Business World Magazine*, December 2003. 47
- [256] World Bank, “World bank development indicators 2011,” tech. rep., World Bank, 2011. 47
- [257] United Nations, “The millennium development goals report 2010,” tech. rep., United Nations, 2010. 47
- [258] N. Suh, *The principles of design*. Oxford University Press, 1990. 48
- [259] C. Mattson and S. Magleby, “The influence of product modularity during concept selection of consumer products,” in *Proceedings of the ASME DETC Design Theory and Methodology Conference*, 2001. 49
- [260] K. S. Thacker, M. Barger, C. Mattson, *et al.*, “A global review of end user needs: Establishing the need for adaptable cookstoves,” in *Global Humanitarian Technology Conference (GHTC), 2014 IEEE*, pp. 649–658, IEEE, 2014. 50
- [261] Engineers Without Borders Canada, “EWB 2013 Failure Report,” tech. rep., Engineers Without Borders Canada, 2013. 51
- [262] Engineers Without Borders Canada, “EWB 2014 Failure Report,” tech. rep., Engineers Without Borders Canada, 2014. 51
- [263] C. Mehta and K. Mehta, “A design space and business strategy exploration tool for infrastructure-based ventures in developing communities,” *International Journal for Service Learning in Engineering, Humanitarian Engineering and Social Entrepreneurship*, vol. 6, no. 2, pp. 30–57, 2011. 51
- [264] “Social lean canvas.” <http://socialleancanvas.com/the-canvas/>. 53
- [265] “Social business model canvas.” <http://www.socialbusinessmodelcanvas.com/>. 53

- [266] K. Pearson, “Note on regression and inheritance in the case of two parents,” *Proceedings of the Royal Society of London*, pp. 240–242, 1895. 54
- [267] C. Spearman, “The proof and measurement of association between two things,” *The American journal of psychology*, vol. 15, no. 1, pp. 72–101, 1904. 54
- [268] M. Kendall and J. Gibbons, *Rank Correlation Methods*. A Charles Griffin title, Edward Arnold, 1990. 54
- [269] G. Lettner and D. McNicholl, “Simple, linear, small-group thinking will no longer cut it,” *EWB Canada 2008 Failure Report*, pp. 19–24, 2008. 56
- [270] W. Miranda, “Impact takes a perfect storm,” *EWB Canada 2009 Failure Report*, pp. 4–6, 2009. 56, 59
- [271] E. Antcliffe, “Agriculture as a business fails to scale,” *EWB Canada 2011 Failure Report*, pp. 12–13, 2011. 57, 59
- [272] I. Smillie, “Failing to learn from failure,” *EWB Canada 2010 Failure Report*, pp. 28–29, 2010. 57
- [273] M. Kennedy and K. Nilsson, “The goat is to be Halal: field-level lessons on scaling community-led total sanitation,” *EWB Canada 2012 Failure Report*, pp. 12–13, 2012. 57, 59
- [274] M. Hemsworth, “Customer service,” *EWB Canada 2010 Failure Report*, pp. 12–13, 2010. 58, 64
- [275] M. Hemsworth, “Protecting innovation in social enterprise,” *EWB Canada 2011 Failure Report*, pp. 18–19, 2011. 59
- [276] O. Scott, “Near term success, long term failure,” *EWB Canada 2010 Failure Report*, pp. 8–9, 2010. 59
- [277] S. Byrns, “The frailty of innovation,” *EWB Canada 2013 Failure Report*, p. 9, 2013. 59
- [278] M. Hird-Younger, “Investing in people and systems,” *EWB Canada 2014 Failure Report*, p. 7, 2014. 59
- [279] S. Hewens, “Introduction: fail to learn,” *EWB Canada 2013 Failure Report*, pp. 4–5, 2013. 60
- [280] N. Jimenez, “Wrong approach to hierarchy and upward feedback,” *EWB Canada 2008 Failure Report*, pp. 11–18, 2008. 61
- [281] M. Klassen, “Insight before influence: the need to stay grounded in the field,” *EWB Canada 2011 Failure Report*, pp. 10–11, 2011. 61
- [282] Malawi Water and Sanitation Venture, “Monitoring, evaluating, and adapting to failure in a complex system,” *EWB Canada 2014 Failure Report*, p. 19, 2014. 63

- [283] C. Robinson, “Internal attachment program: monitoring and evaluation failure,” *EWB Canada 2013 Failure Report*, pp. 18–19, 2013. 64
- [284] S. Grant, “Hiring local staff: a past mistake from previous work in the Philippines,” *EWB Canada 2008 Failure Report*, pp. 7–11, 2008. 65
- [285] D. Boland, “Lessons learned in district selection,” *EWB Canada 2011 Failure Report*, pp. 14–15, 2011. 65
- [286] M. Fuge and A. Agogino, “Pattern analysis of ideo’s human-centered design methods in developing regions,” *Journal of Mechanical Design*, vol. 137, no. 7, p. 071405, 2015. 69, 153
- [287] P. J. Zimoch, E. Tixier, A. Joshi, A. Hosoi, and A. G. Winter, “Bio-inspired, low-cost, self-regulating valves for drip irrigation in developing countries,” in *ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2013. 69
- [288] B. M. Judge, K. Hölttä-Otto, and A. G. Winter, “Developing world users as lead users: A case study in engineering reverse innovation,” *Journal of Mechanical Design*, vol. 137, no. 7, p. 071406, 2015. 70, 153
- [289] N. G. Johnson and K. M. Bryden, “Field-based safety guidelines for solid fuel household cookstoves in developing countries,” *Energy for Sustainable Development*, vol. 25, pp. 56–66, 2015. 71
- [290] A. E. Wood, C. D. Wood, and C. A. Mattson, “Application and modification of design for manufacture and assembly principles for the developing world,” in *Global Humanitarian Technology Conference (GHTC), 2014 IEEE*, pp. 451–457, IEEE, 2014. 72
- [291] Engineering for Change (ASME, IEEE, EWB), “Introduction to Engineering for Global Development.” <http://www.engineeringforchange.org/what-we-do/intro-to-egd/>. Accessed: 2016-FEB-16. 80
- [292] C. Mattson and A. Winter, “Why the developing world needs mechanical design,” *Journal of Mechanical Design*, vol. 138, pp. 070301–3, 2016. 80
- [293] V. Lofthouse, “Social issues: Making them relevant and appropriate to undergraduate student designers,” *Design and Technology Education: an International Journal*, vol. 18, no. 2, 2013. 80
- [294] K. S. Thacker, M. Barger, and C. A. Mattson, “A more balanced design approach for preserving the usability of a peruvian cookstove,” in *ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pp. V02AT03A045–V02AT03A045, American Society of Mechanical Engineers, 2015. 81
- [295] N. Furr and P. Ahlstrom, *Nail it then scale it: the entrepreneur’s guide to creating and managing breakthrough innovation*. Nathan Furr and Paul Ahlstrom, 2011. 81
- [296] N. MacCarty, *A zonal model to aid in the design of household biomass cookstoves*. PhD thesis, Iowa State University, 2013. 81

- [297] N. G. Johnson, M. Bryden, and A. Xiao, "Risk analysis and safety evaluation of biomass cookstoves," in *ASME 2005 International Mechanical Engineering Congress and Exposition*, pp. 185–191, American Society of Mechanical Engineers, 2005. 81
- [298] D. L. Van Bossuyt, *Mechanical engineering design across cultures: a method of designing for cultures*. PhD thesis, Oregon State University, 2008. 81
- [299] W. Perry, A. Broers, F. El-Baz, W. Harris, B. Healy, W. D. Hillis, *et al.*, "Grand challenges for engineering," *National Academy of Engineering, Washington, DC*, 2008. 83
- [300] Environmental Protection Agency, "Water efficiency in the commercial and institutional sector: Considerations for a WaterSense program." http://www3.epa.gov/watersense/docs/ci_whitepaper.pdf, 2009. Accessed: 2016-FEB-29. 83
- [301] R. K. Yin, *Case study research: Design and methods*. Sage publications, 2013. 84
- [302] A. Stewart, *The ethnographer's method*, vol. 46. Sage, 1998. 108, 114
- [303] A. S. Sarvestani, L. Bufumbo, J. D. Geiger, and K. H. Sienko, "Traditional male circumcision in uganda: a qualitative focus group discussion analysis," *PloS one*, vol. 7, no. 10, p. e45316, 2012. 110
- [304] A. S. Sarvestani and K. H. Sienko, "User-based design approach to develop a traditional adult male circumcision device," *Journal of Medical Devices*, vol. 7, no. 2, p. 020927, 2013. 110
- [305] I. Mohedas, A. Sabet Sarvestani, S. R. Daly, K. H. Sienko, *et al.*, "Applying design ethnography to product evaluation: A case example of a medical device in a low-resource setting," in *DS 80-1 Proceedings of the 20th International Conference on Engineering Design (ICED 15) Vol 1: Design for Life, Milan, Italy, 27-30.07. 15*, 2015. 110
- [306] C. Kramsch, *Language and culture*. Oxford University Press, 1998. 111
- [307] B. Berg and H. Lune, *Qualitative research methods for the social sciences*. Pearson Education, 2013. 114
- [308] J. Lofland and L. H. Lofland, *Analyzing social settings*. Wadsworth Publishing Company Belmont, CA, 2006. 116
- [309] C. Juliet and A. Strauss, *Basics of qualitative research*. Thousand Oaks, CA: Sage, 2008. 116
- [310] L. Dahlberg and C. McCaig, *Practical research and evaluation: a start-to-finish guide for practitioners*. Sage, 2010. 116
- [311] T. Cole, "Too many digits: the presentation of numerical data," *Archives of disease in childhood*, pp. archdischild–2014, 2015. 124
- [312] D. N. Beede, T. A. Julian, D. Langdon, G. McKittrick, B. Khan, and M. E. Doms, "Women in stem: A gender gap to innovation," *Economics and Statistics Administration Issue Brief*, no. 04-11, 2011. 142

- [313] C. Mattson and C. Sorensen, *Fundamentals of Product Development*. CreateSpace Independent Publishing Platform, 2013. 160
- [314] K. Ulrich and S. Eppinger, *Product design and development*. McGraw-Hill/Irwin, 2004. 160
- [315] A. E. Wood and C. A. Mattson, “A method for determining customer needs in the developing world,” in *ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pp. V02AT03A047–V02AT03A047, American Society of Mechanical Engineers, 2014. 160