Aligning Stakeholder Interests: From Complex Systems to Emerging Markets

by

Jesse Austin-Breneman

Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Mechanical Engineering at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY September 2014

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Signature redacted

Author

Department of Mechanical Engineering
August 15, 2014

Signature redacted

Certified by....

Maria C. Yang
Associate Professor
Thesis Supervisor

Signature redacted

Accepted by .................................................................

David Hardt
Chairman, Department Committee on Graduate Theses
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Abstract

Design often requires balancing competing objectives from a variety of stakeholders. From the design of large-scale complex engineering systems to the design of end-user products for emerging markets, managing the trade-offs between different objectives from a systems-level perspective is a key challenge for design teams. This thesis investigates differences between how formal strategies can be used to balance trade-offs and how practitioners currently perform this task. Through the use of interviews, case studies, and field and laboratory experiments, this thesis seeks to examine how real-world designers approach these problems. The work investigates practitioner strategies and analyzes them to gain a better understanding of how human design teams operate. These insights are then used to inform proposed guidelines for performing design tasks in these contexts. First, observations of practitioners in space system design lead to a new way of modeling interactions between sub-systems. Then, interviews with designers working on products for emerging markets are used to formulate a new methodology, Design for Micro-Enterprise, that focuses on the needs of small-scale entrepreneurs. Results from the analysis suggest that focusing on a micro-entrepreneur’s business strategy may be a successful approach to balancing both the end-user and supply chain requirements in these markets.

Thesis Supervisor: Maria C. Yang
Title: Associate Professor
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Chapter 1

Introduction

The design of complex systems and products often requires the designer or design team to balance competing objectives to create a solution which satisfies multiple stakeholders. This work examines how practitioners manage these tradeoffs in order to improve formal strategies for balancing stakeholder interests during the design process in different contexts.

1.1 Motivation

This work is motivated by recent trends towards increasingly complex engineered systems and products. These projects require design teams to balance complex sets of considerations using a wide range of design and decision-making skills. Formal approaches for optimizing complex systems offer strategies for arriving at optimal solutions in situations where system integration and design optimization are well-formulated. However, in many cases, such formulations do not exist and are difficult to produce, such as in emerging markets. This work seeks to better understand how current practitioners manage these trade-offs in order to improve formal methods and suggest new directions for practice in a variety of settings.

One motivation for this work is the interaction of stakeholder interests in the design of complex systems, such as orbital satellites. The design of complex engineered systems is typically conducted by interdependent, multidisciplinary subsystem design
teams. An ongoing challenge in system design is how to distribute limited resources among a set of subsystems and effectively integrate the subsystem into overall system. For example, managing the tradeoff between mass and power throughout the many sub-systems of a satellite, while maximizing the overall system performance. This situation is further complicated by the increasing use of distributed teams to design these systems [1] which presents communication and team cohesion problems for collaboration [2]. Formal methods offer some strategies for navigating these challenges but rely heavily on the skills and ability of the individual designer. This work seeks to examine how practitioners currently address these issues and examine how their current strategies affect design outcomes in real-world situations. These behaviors can then be compared to understand how differences can be used to improve both the generation of more realistic formal models and improve real-world approaches to system design.

Another important motivation is the growth in product design for emerging markets and the relative lack of success in these markets. Mature markets in industrialized countries have led Multi-National Corporations (MNCs) to look for growth in these areas. Although individual consumers in these markets have extremely limited buying power, the sheer size of the market makes these opportunities attractive to a variety of organizations [3, 4, 5]. The growth in products for these markets has been driven by "the potential of serving an unserved market and alleviating the level of global poverty while still earning a profit [6]." However, there is a dearth of successful products in this area and many high-profile failures. One study reports that less than half of companies entering these markets meet their own goals [7]. This can be compared to a new product failure rate at launch of 33% in mature markets [8]. Other literature has also pointed to mixed results from MNCs working in emerging markets, with many operating at a loss [6].

These product failures can be attributed to many factors, but design literature points to a fundamental misunderstanding of the users [3, 9]. This type of failure is common, perhaps as Bonsese suggests inevitable, during remote design when the users are geographically separated from the designer [10, 11]. Customer Value Chain
Analysis is one example of a technique that emphasizes the importance of stakeholder analysis and balancing competing objectives in this area [12].

From complex engineered systems to the complex socio-technical systems of emerging markets, this work seeks to analyze and propose structured design processes that incorporate lessons from how practitioners balance competing objectives. The insights from practitioners can then be used to propose guidelines for performing design tasks in these markets.

Chapter two outlines the body of literature from which the work draws. Chapter three describes how teams performing complex system design balance competing objectives throughout the design process. Interviews with practitioners are presented as well as simulations using Multi-Disciplinary Optimization (MDO) techniques. Chapter four describes the development of a proposed set of guidelines for approaching product design in emerging markets, Design for Micro-Enterprise. Interviews with practitioners and case studies of products designed for use by micro-entrepreneurs in emerging markets are used to motivate the framework. Chapter five presents results from a field experiment involving interviews of micro-entrepreneurs of a public toilet franchise in East Africa. These results are used to further refine the Design for Micro-Enterprise approach. Chapter six summarizes the work and presents directions for future research.

1.2 Related Work

This work draws on work in formal strategies for system design as well as work in team behavior and design for emerging markets. This body of literature comes mainly from design research literature but also includes contributions from business literature, psychology, sociology and economics. The literature outlined below is split into three sections: general models of design, design of complex systems, and design for emerging markets.
1.2.1 Structured Design Process Models

There is a rich body of literature studying design process. Many researchers have modeled the engineering design process, from Pahl and Beitz [13] to Ulrich and Eppinger [14]. These models can act as guidelines for practitioners, a prescriptive method for performing design, such as Design for X strategies described below. They also form the starting point for researchers investigating the effect different factors have on the design process [15]. These models share a goal of making the design process explicit in order to test and validate different strategies. However, while they differ in their description of the methods, they all in general propose strategies for defining functional requirements, generating embodiments to fulfill those requirements, testing and refining those embodiments, and then iterating through the process until meeting some stopping condition. This work focuses on how competing stakeholder objectives affect these tasks in real-world design situations.

Stakeholder Analysis

This work uses structured design process models as a framework for understanding design practice. In particular, the definition of stakeholder and stakeholder analysis is crucial to this work. Although some areas of research define stakeholders as the different users engaged with a product [16], this thesis will be using a more expansive definition to include anyone involved in the design, use, or delivery of the product [10]. This includes the manufacturer, the designer, the end-user, other manufacturers and distributors along the supply chain, government actors, and secondary users. In the case of non-profit organizations working in emerging markets there may also be different funding sources. All of these actors have different objectives and are affected by design decisions.

Studies of Team Behavior

This thesis focuses on how teams of human designers solve system design problems. There is an extensive body of literature on human decision-making and commu-
cation and how it affects team performance from the fields of organizational behavior, psychology and sociology. Because system design is commonly performed by teams, the most relevant research in this area tests factors which affect team success across an array of interdisciplinary problems. Nardi and Whittaker [17] emphasize the need for a shared team understanding for social communication. They investigated the importance of face-to-face communication in distributed design situations. Similarly, networking in the physical space of collocated teams has been shown to be an important determinant for design quality [18]. Team communication is also addressed in the area of team cognition. Cooke and Gorman [19] demonstrate several measures using communications as a method for understanding the team decision-making process and its ability to accomplish high-level processing of information and reach an optimal decision. This paper draws on these works to provide a framework for understanding and modeling team communication in a more effective manner.

User-Centered Design

This thesis examines how real-world designers approach trade-offs. As such it draws on the wide range of existing literature on user-centered design. One common design framework divides design approaches into technology-push and market-pull approaches [20]. A technology push approach takes a new process, artifact or material and attempts to find a use for it. Market pull approaches, by contrast, seek to design solutions to existing customer needs or requests. These market-pull approaches can be broadly categorized as user-centered design strategies, as they use customer-satisfaction and fulfillment of user needs as the main metric for product success. User-centered design is widely used in both industry and research [21], from user experience design [22] to complex system design [23].

Design for X strategies

This work proposes a structured design process methodology, which follows the well-established Design for “X” (DFX) literature. These methodologies provide prescriptive guidelines for practitioners to support them throughout the design process and help
them evaluate design decisions. Holt and Barnes provide an overview of a range of DfX methodologies including Design for Assembly, Design for Manufacture and Design for Environment [24]. Design for Assembly, for example, helps designers create products with minimal assembly time and costs. Other strategies include Design for Quality [25], Design for Maintenance [26], Design for Remanufacturing [27] and Design for Cost [28]. All of these methods support the designer in making decisions regarding one aspect of product outcomes. In this work, these will be used to model guidelines for designing for micro-entrepreneurs.

1.2.2 Complex System Design

This work draws on an extensive body of literature in complex system design and design process modeling. This work also uses previous work in simulations of complex system design using optimization techniques. Research in team behavior, including negotiation and communication, is also presented.

Structures for system-level design

Large engineering systems are traditionally broken down into functional hierarchies. For example, an aircraft design can be broken down into structures and propulsion subsystems, with overlapping but not identical design parameters [29]. Furthermore, each subsystem can have thousands of input variables. In the classical approach to problems of this type, each subsystem is designed independently by discipline with system-level iterations occurring periodically throughout the process [30]. New systems-level approaches have been developed to increase the speed and effectiveness of the design process [31]. Industry has been quick to adopt systems-level approaches to interdisciplinary design [30, 31, 32, 33].

Design process models for complex systems

A metamodel is one tool used to quickly explore design spaces and converge to an optimal set of solutions. Metamodels either evaluate or approximate subsystem response
to design parameter inputs. By generating system-level design outputs by integrating subsystem responses, the models can systematically search the design space and help guide designers towards an optimal design outcome. A limitation stems from the ability of the metamodel to accurately and quickly approximate the subsystem response to design inputs. These tools reflect a balance between local and global knowledge of the system as defined by Papalambros [34]. Designers rely on their expert knowledge of the global design space for validating approximations as they create simplified subsystem models. The numerical algorithms rely on local knowledge at each iteration to make decisions about the "best" direction to search. Simpson, et al. [35] present a wide range of problems that can be addressed through metamodels and associated algorithms. Sobieszczanski-Sobieski and Haftka’s survey [36] demonstrates the range of applications in the aerospace industry.

One branch of research uses these methods to model the complex system design process. Game Theory is one approach for modeling the multidisciplinary design process and was first proposed by Vincent [37] and further developed by Lewis and others [38, 39]. Game Theoretic design attempts to identify a rational design called Nash Equilibrium [40] given limits to the amount and form of information being passed between designers. The resulting designs may differ depending on the type and quantity of information exchanged. Thus, the resulting designs will be rational given limited information, but will not necessarily result in an optimal design. These traditional game theoretic approaches have further been combined with Decision-Based Design [41] and adopted in a broad range of design research [42, 43, 44] to become a prominent framework for the study of multidisciplinary design problems [45]. The complex system design process can also be viewed as a multi-objective optimization problem. Multi-disciplinary Optimization (MDO) is one approach which utilizes this philosophy and also introduces a facilitator to manage decision-making among the group [46]. Design researchers draw from this literature to appropriately model their particular instance of complex system design.
Team structure

Key components common to all of the metamodels are 1) the team structure or roles (i.e. the "direction" and "order" in which information is passed), 2) the form of the information passed between subsystems (such as point design and local sensitivities) and 3) how each subsystem makes decisions and trade-offs. This paper explores the last of these elements. Simulations have allowed researchers to observe the effect of changes, at an abstract level, in team structure, information passed and individual decision-making on performance metrics such as the speed and accuracy of the optimization. Yi, et al. [47] compare seven MDO approaches with different hierarchical team structures. MDO models rely on a system facilitator who will make optimal trade-offs that will benefit the overall system. Ciucci, et al. [48] compared different team structures, including Game Theoretic and MDO approaches. Lewis and Mistree presented a Game Theoretic approach where each agent is involved in the optimizing task. Agents made decisions using a compromise decision support problem [29]. In doing this type of analysis, researchers have suggested best practices for design processes. Collopy outlines a strategy for reaching an optimal design based on passing of gradient information [49].

Negotiation in Complex System Design

Negotiation in the context of engineering design is a topic with contributions from a variety of fields including design research, management science, economics and psychology. Smith and Eppinger [50] present a method utilizing a Work Transformation Matrix to help design teams identify controlling features of a physical design and which subsystems will require more iterations than others. Yassine and Braha [51] present a method using an information exchange model to help subsystems represent complex task relationships better when negotiating. Yassine et al. [52] also examines the phenomena of information hiding in complex system design. This occurs when local subsystem optimization and system-level optimization occur asynchronously and information gained from the local development is hidden from the system-level pro-
cess. Klein, et al. [53] model the effect of the team or network structure on the negotiations during the complex system design process. Di Marco, et al. [54] examined the effect of individual team member culture on the negotiation process in complex system design teams. This paper draws on these sources to help model the negotiation between subsystems.

**Problem Selection**

A key issue in validating and understanding results of simulations of the design process is the selection of test problems. Coello, et al. [55] categorize the types of multi-objective optimization test problems and provide an overview of existing test suites. This work is part of a larger body of literature addressing many of the issues involved in developing appropriate test suites [56]. It should be noted that test suites can be useful for comparing and evaluating optimization algorithms but may not be representative of algorithm performance on "real-world" problems. In order to gain the maximum insight from the simulations, a test suite should be comprised of a variety of types of problems. This paper draws from several sources to incorporate as many different types of test problems as possible.

**1.2.3 Design for Emerging Markets**

**Studies on Product Design in Emerging Markets**

There has been a recent focus on emerging markets in the design research community. Many methodologies have been developed by practitioners and researchers in this field to create products for these markets, including customer value chain analysis [12], design for the base of the pyramid (BoP) [57], the product service system approach [5], design for sustainable development [58] and design for emerging markets [59, 9]. Both Prahalad and Chavan explore the different ways the market can be divided and how the strategies differ in perspective and target user [60, 9]. Regardless of strategy used, there have been many high-profile failures in this area.
**DFX Strategies for Emerging Markets**

This work presents Design for Micro-enterprise (DfME), a structured design process methodology, which draws from DFX literature, particularly those methods developed specifically for emerging markets. Design for the BoP and related methodologies are a subset of DFX meant to help designers create products that sustainably improve the livelihood of people who do not have their needs met [10]. Similar strategies, which have the same goal but approach it from different perspectives, include the Product Service System approach [5], Design for Extreme Affordability [11] and Design for the Bottom of the Pyramid [9, 62].

**Business-to-Business Relationships**

Due to its focus on entrepreneurship, Design for Micro-enterprise also incorporates lessons from business literature. In particular, DfME highlights the differences between Business-to-Business (B2B) and Business-to-Consumer (B2C) transactions as a way to evaluate design decisions. Mudambi demonstrates how service and branding are important to B2B markets in differentiating competitors [63]. Lam makes a similar connection between service and customer loyalty in B2B [64]. In fact, intangible characteristics such as customer perception of service quality and brand image have been shown to be more important than product features in some B2B situations [65]. Less has been written specifically about B2B transactions in emerging markets, but service has been cited as an important strategy for companies looking for an advantage in emerging markets [3, 60].

**Effects of Design Process Focus**

The Design for the BoP approach has proven to be a useful way of thinking about early stage design, but Donaldson highlights the need for methods that consider the distribution, manufacture or service of the products [10]. These factors may ultimately have more of an impact on the success of the product. Fathers also notes that the wide-spread use of remote design and short-term consultancies in this field...
may make it difficult to practice user-centric design, especially in a cross-cultural setting [11].

Design for Micro-enterprise seeks to address these critiques by integrating lessons from B2B markets. Shifting the focus from a consumer product to a commercial relationship also addresses many of the concerns raised about the original design methods in this area. DME is meant to be practiced in a design team where design decisions support both user-centered design as well as business requirements such as service, distribution and production. The guidelines are intended to help the designer collaborate with the business and logistical members of the team and produce concepts with a higher chance of success in emerging markets.

**Entrepreneurship in Emerging Markets**

Another critique of Design of BOP centers on the definition of "entrepreneur." Although a large percentage of the workforce in emerging markets is made up of self-employed individuals, this does not necessarily mean that they behave in a manner similar to "entrepreneurs" in a more mature markets. Banerjee and Duflo describe the behavior of the "reluctant entrepreneur [66]." In their work they demonstrate that people who own small businesses in emerging markets may not have the same motivations or risk profiles as those in more mature markets and are therefore less likely to take risks to grow their business. Therefore, products or design strategies predicated on the customer acting "entrepreneurially" should take into account this different behavior profile.

**Product Attributes**

Literature has identified a variety of factors which users use to evaluate products. Garvin proposed eight dimensions of quality for consumer products: performance, features, reliability, conformance, durability, serviceability aesthetics and perceived quality [67]. Other characteristics previously studied include cost, trust in brand, availability, service relationship, multi-functionality and modularity. Researchers have also investigated how users self-identification, for example as environmentalists,
affects product purchasing decisions [68]. Another important framework for understanding how product attributes affect user preferences is the adapted Kano model of customer satisfaction from Matzler, see Figure 1-1[69, 70]. The diagram shows the correlation between customer satisfaction and need fulfillment. Features or attributes that place a product above the upper curve are known as “delighters,” while those below the lower curve are defined as “must-haves.” This section draws heavily on all of these works to both define and categorize product attributes and their affect on user preferences.

Figure 1-1: Adapted Kano Model of Customer Satisfaction
Product Purchasing Decisions

There is a large amount of literature regarding purchasing decisions in both the engineering and economics fields. Many factors affecting user purchasing decisions have been studied, including in emerging markets. Studies have shown the importance of the information pathway, or where the user learned about the product [71, 72, 73]. Risk preferences are another area of research, with procrastination [66] and individual risk profiles [74] both affecting technology adoption rates in emerging markets. Demographic factors, such as variable fixed costs [75], varying levels of business knowledge [76, 77] have been shown to affect product purchasing decisions of entrepreneurs in emerging markets. Foster, et al. survey factors affecting technology adoption [78]. This section also draws from literature regarding franchises, in particular the models of moral hazard in franchising [79].

1.3 Research Gap

In structured design process literature, how to manage trade-offs is an important part of the any design approach. In complex system design, methods such as MDO place a team-member in charge of taking a systems-level view of the problem. In contrast, the majority of methodologies developed for design for emerging markets focus the designer’s attention solely on the end-user needs. Some, such as customer-value chain analysis, notably encourage a more system-level view of the design task. However, these strategies do not elucidate how to incorporate all of the competing stakeholder needs into the final design. This thesis uses investigations of real-world design practice to gain a better understanding of how design teams are currently performing this crucial task and to suggest new directions and guidelines for achieving this balance in the future.
1.3.1 Research Questions

There is a wide range of research in both formal strategies for design, such as MDO and more practical guidelines such as Design for X strategies. These areas include theoretical frameworks for modeling design process and qualitative investigations of design practice. This work seeks to use these tools to investigate how practitioners currently approach balancing stakeholder interests throughout the design process and how to improve this part of the process.

This work seeks to answer the following questions:

1. How do practitioners currently balance competing objectives in complex systems with many stakeholders?
2. How do these practices change given the context of the complex system?
3. How does the human decision process for balancing competing objectives differ from formal strategies?
4. What is a successful approach to balancing stakeholder interests throughout the design process?
Chapter 2

Designer Behavior in Complex System Design

In this chapter, the balancing of competing objectives will be examined within the context of complex system design. The chapter focuses on the differences between formal strategies for complex system design, particularly the integration of sub-systems and human decision-making strategies. The first section presents findings from interviews with a large aerospace organization. In the second section, their findings are used as the basis of a set of models.

2.1 Biased Information Passing in Complex System Design

This section investigates ways in which negotiations within human design teams differ from when formal methods are used. Results from a series of interviews of sub-system and system-level designers are presented and then modeled using mathematical simulations.
2.2 Motivation

Mathematical simulations are one type of tool used to simulate design space exploration and optimization of complex systems. They can be used to explore the impact of the factors mentioned above. Simpson, et al. present a wide range of problems that can be addressed through these mathematical models and associated algorithms [35]. Simulations are also used to evaluate formal design approaches. Sobieszczanski-Sobieski and Haftka's survey [36] demonstrates the range of applications in the aerospace industry. Key components common to and studied by these simulations are 1) the team structure or roles, 2) the form of the information passed between sub-systems and 3) how each sub-system makes decisions and trade-offs. However, these models may not accurately reflect how actual design teams perform these tasks.

Previous work in understanding differences between formal strategies and human design teams demonstrated that the human decision-making process of student teams greatly differed from the formal methods in sub-optimal ways [80]. This work seeks to extend that research by examining expert human design teams in an industry setting. Teams populated by expert designers and engineers may behave differently than the student teams. Finally, by examining the process in an industry setting a better understanding of the types of problems formal methods need to address may be reached.

This section presents results from a number of interviews conducted of sub-system and system-level practitioners within one organization in the aerospace industry. The interviews focused on how real-world human decision-making process differed from formal design strategies. The intent was to understand how subsystems would reach agreement with each other as part of an overall system design, and what strategies were used in deciding how to share and pass information.

This study consisted of two distinct phases. The first part used an interview-based methodology to develop insight and describe the behavior of inter-disciplinary design teams performing complex system design in the aerospace industry. Based
on the results of the interviews, the second part utilized formal multi-disciplinary optimization techniques to simulate the described behavior of subsystems negotiating to a system-level optimum.

This study seeks to answer the following questions:

1. What strategies do real-world aerospace designers and engineers use when negotiating design parameters with other sub-systems?

2. What impact might these strategies have on system-level optimality?

3. What impact might these strategies have on the speed of system optimization?

Speed and optimality are important indicators for comparing optimization algorithms and can lead us to a better understanding of the impact of the real-world strategies described. Are these strategies an issue that should be considered and if so can we develop processes robust to this type of behavior?

2.2.1 Research Gap

This research focuses on the interactions between subsystems in complex system design. Current literature either focuses on improving mathematical formulations of formal models of the design process or developing qualitative frameworks of team behavior. This research seeks to bridge the gap between the two and use the power of both approaches to gain a better understanding of how subsystems interact in complex system design tasks. In particular, this study hopes to both improve the effectiveness of the simulations by more realistically modeling the social component of human behavior and to improve the qualitative frameworks by quantifying the estimated effect of the human factors.
2.3 Phase 1: Interviews with Practitioners

2.3.1 Interview Methods

The interview phase consisted of twelve on-site interviews with lead subsystem designers and system integrators within a large aerospace organization. Subsystem designers were drawn from a diverse set of sub-systems such as structures, propulsion, avionics, guidance and navigation control, materials and manufacturing, systems integration, operations, liquid engines, and testing.

Each interview consisted of an hour of open-ended discussion on system integration management and inter-subsystem communication. The primary question asked was, "How do you manage the integration of your sub-system with other sub-systems?" Biographical information such as job title and description were also recorded. The designers shared design artifacts to illustrate different concepts. The interviews were not recorded due to confidentiality. Notes were taken separately by two investigators. Select quotes and themes from the interviews are presented below. These concepts were incorporated into and informed the second phase of the study.

2.3.2 Interview Results

Finding #1: Structure of Negotiations

The interviewees describe a number of modes of interacting with other sub-systems. The notable finding is that their patterns of interactions could be characterized fairly well in the formal terminology of MDO and Game Theoretic models depending on the level of agreement between the sub-systems. The basic mode of negotiation followed a Game Theoretic model, with subsystem designers connecting with their counterparts in other sub-systems to manage trade-offs on an informal level. Larger disputes were negotiated following an MDO model with disagreements between sub-systems settled by a committee of upper management.

All ten sub-system designers mentioned direct personal relationships as a conduit for negotiation with designers in the other sub-systems they interfaced with regularly.
One example of this type of negotiation is the "volume envelope" mechanism. One sub-system set "envelopes" or volumes other sub-systems could use as a volume constraint early in the design process. If another sub-system needed more space, the sub-system designer first went to sub-system designers of nearby envelopes to reach a compromise on the volume needed.

A similar negotiation happened with respect to power requirements. Power requirements for one sub-system were negotiated between the appropriate level of sub-system designer early on and then adjustments and compromises were made throughout the process. This is facilitated by the placement of personnel near each other. Engineers from other sub-systems have offices or "sit" in the relevant sub-system office suite.

Compromises are also facilitated by engineers designated as leads for integrating subsystems. These engineers are representatives from the different sub-systems and negotiate at a more formal level during planned meetings. A three level structure of negotiation was proposed by several of the designers. The lowest level is within the sub-system; this happens routinely on a daily basis and focuses on optimizing the sub-system and setting requirements. Most of the negotiation of tolerances and requirements happens at a cross-cutting second level. Two engineers independently estimated that 80-90% of issues raised were resolved at this level. The third level involves upper management and a formal conflict resolution process. For example, a disagreement between two sub-systems which could not be resolved at either of the two lower levels could be brought before the weekly chief engineers' meeting and a panel of upper management would then make a decision. These levels were described by multiple participants as "down and in" and "up and out" exemplifying the correlation between level of formality and interaction within or without the team.

The higher level of resolution follows a MDO model of negotiation. Sub-systems no longer negotiate between themselves, but bring it to a system integrator who makes a decision. This view was supported in the interviews with the system integrators. One system integrator described his role as "finding problems and fixing them." Another difference between the self-reporting on the levels was the formality. The
levels increase in formality with the third level requiring documentation of the conflict and a presentation of both sides of the issue before a panel of upper managers. All such third level conflicts are tracked throughout the process and system integrators are required to resolve them at different major milestones. This is in stark contrast with the informality of the second level at which sub-system designers simply make changes by talking to another sub-system designer. Estimates for the relative amount of problems which reached the third level ranged from 2 to 5%. All sub-system designers expressed their trust in the upper management board to resolve conflicts in an optimal way.

Finding #2: Biased Information Passing Over Time

Another aspect of negotiation that arose in the interviews was the concept of biased information passing. The phrase “margins” was used by interviewees to refer to the practice of reporting “conservative” parameters to other sub-systems during the negotiation process. Their definition of “margins” is distinct from the formal definition of risk or performance margins detailed in the related work section. In these cases, the “conservative” estimates of the parameters are used as a negotiation tool between sub-systems and do not necessarily reflect the level of uncertainty attached to the design parameter. The phrase “keeping something in my back pocket” was used independently by a majority of the sub-system designers to describe this issue. For example, one sub-system designer highlighted the use of conservative estimates in the development of the budget for a previous project. The sub-system built an extra 30% cushion into their budget estimate as an insurance policy against future budget cuts. The cushion consisted of “budget off-ramps” or extra tests and tasks that were not strictly necessary and could be cut easily near the end of the project. This structure was due to the sub-system designers belief they would be later asked to cut down their budget, thus the higher budget at the outset offsetting future losses. One interviewee reported that conservative estimates were one factor which contributed to cost overruns and negative consequences for the project. A similar practice was used with parameters that interfaced between sub-systems such as mass, volume and estimated
time to completion of a task. One of the engineers reported that estimated mass was reported with a 30% cushion at the outset, which was reduced over time to 10% near the final design review to allow for negotiation.

It should be noted that this practice is not necessarily sub-optimal, and can lead to highly robust systems. However, many of the participants felt that the practice had some negative effects. The most common example raised was both parties being conservative in a negotiation and reaching a highly sub-optimal compromise. Some sub-system designers believed large design decisions, such as the switch in the overall structure of one project to a common bulkhead, were based on overly-conservative estimates and led to major cost overruns. System integrators also discussed the difficulty in obtaining accurate information from sub-systems. One system integrator discussed how conservative estimates in both the inputs as well as the system models used by the sub-systems led to cost and schedule failures. They also reported the use of formal risk mitigation procedures which can be inaccurate when presented with conservative inputs.

2.4 Phase 2: Simulations of Real-world Behavior

2.4.1 Simulation Structure

The simulation phase consisted of the development of a series of MDO simulations aimed at recreating and quantifying the themes introduced in the interview process. The main purpose of the simulation phase was to simulate the behavior of "margins" or biases and quantify the effect on system optimization. Simulations were performed on a two-player system to simplify initial calculations.

The interview results suggested that the organization's design team uses a sequential design optimization architecture, also known as fixed-point iteration [81]. In this portion of the study a series of optimization simulations were created to mimic this design process. Only a two-player system was considered for demonstration of the core concept. The two-player system consisted of two subsystems each with their own
objective function. Optimization was performed sequentially with the first subsystem optimizing its design parameters and then passing point design information to the second subsystem. The second subsystem then minimized its design parameters based on this information. The second subsystem then passed point design information back to the first subsystem completing a single system iteration. This is presented in Figure 2-1.

\[
\begin{align*}
\text{Sub-System 1} & : \quad \min_{x_1, x_2} f_1(x_1, x_2, x_3) \\
\text{Sub-System 2} & : \quad \min_{x_3} f_2(x_1, x_2, x_3)
\end{align*}
\]

Figure 2-1: System schematic for one iteration

The concept of biases is introduced in the passing of point design information between subsystems. The simulations were performed in three different conditions: no bias, static bias and decreasing bias. In the first condition no bias was used and point design information was passed normally as in traditional MDO processes. In the static bias condition, the point design information was multiplied by 1.3 during the transfer to the other subsystem to reflect an added bias of 30%. This number was chosen based on the estimates reported in the interviews. Each subsystem was in effect biasing the information passed by 30% in the same direction at every iteration. In the decreasing bias condition, the bias was decreased after each system iteration. The design point information was multiplied by \( b = 1.3 - 0.1t \) for \( t = 0, 1, 2, 3, \ldots \) \& \( b \geq 1 \). This again reflects information reported during the interview process. Subsystem designers reported the bias was decreased 30% to 0% in 10% increments at each design review.

These three conditions were simulated on a test suite of two-objective problems drawn from Multi-objective Evolutionary Algorithms by Coello, et al. [55] and from a test suite proposed by Deb, et al. [56]. This test suite was chosen for its variety in the type of problems provided. Three sets of problems were tested: unconstrained multi-objective test functions(MOP2-MOP7), side-constrained multi-objective test
functions (MOPC1,MOPC3), and generated multi-objective test functions (DTLZ1-
7). It is well-understood that test suites do not necessarily reflect real-world behavior. However, test suites can be used to provide a base level of comparison between algorithms. This was important in this study to allow for comparison between the three conditions.

For example, one problem tested was Multi-objective Problem 4 (MOP4) from Coello, et al. [55]. This test problem set $f_1$ and $f_2$ as follows:

$$f_1(x) = \sum_{i=1}^{n-1} (-10e^{-0.2}\sqrt{x_i^2 + x_{i+1}^2})$$

$$f_2(x) = \sum_{i=1}^{n} (|x_i|^{0.8} + 5\sin(x_i)^3)$$

with $-5 \leq x_i \leq 5$ for all $i \leq n$, where $n$ is the number of decision variables. In this case, $n = 3$. One iteration of the simulation, as shown in Figure ??fig:oneiter), would involve picking a random starting point $\vec{x} = (x_1, x_2, x_3)$ that is within the bounds $-5 \leq x_i \leq 5$. The first subsystem would then minimize the function $f_1$ with respect to $x_1$ and $x_2$, generating a new design point $(\vec{x}_1, \vec{x}_2)$. This design point would be multiplied by the bias factor $b$ and passed to Sub-system 2. Sub-system 2 would hold the new vector $(b\vec{x}_1, b\vec{x}_2)$ constant and minimize $f_2$ with respect to $x_3$, generating a new design point $\vec{x}_3$. The final design point after one iteration would be the vector $(b\vec{x}_1, b\vec{x}_2, b\vec{x}_3)$. For the second iteration, Sub-system 1 would use $(b\vec{x}_3)$ to minimize $f_1$ with respect to $x_1, x_2$ and start the process over again. This would repeat until a stopping condition was met. Depending on the bias condition being tested, $b = 1, b = 1.3$ or $b = 1.3 - .1t$ where $t = 0, 1, 2, 3 \ldots$ & $b \geq 1$ and $b$ changed after each iteration.

Comparison between the different conditions was made along two metrics, optimality and speed. These are two common metrics used for comparing algorithms [55]. Optimality was measured using the Euclidean distance of the final system design from the Pareto Frontier after satisfying the stopping condition. The stopping condition was
defined as either convergence for both subsystems $f_1(i) = f_1(i - 1); f_2(i) = f_2(i - 1)$ or reaching a Nash Equilibrium $f_1(i) = f_1(i - 2); f_2(i) = f_2(i - 2)$. The Pareto Frontier for these test problems was often given as an analytical solution in the test suite. If not available, the Pareto Frontier was calculated using the MATLAB Genetic Algorithm function GAmultiobj. Speed was measured by the number of iterations until the stopping condition was met. The minimization of each subsystem was performed using the MATLAB optimization function f_mincon with the interior-point algorithm.

Several parameters were varied at each condition. A variety of starting points were tested for each condition and test problem to check for robustness to initial conditions. The order of sequential optimization was also varied for each testing condition. This checked whether having the first or second subsystem optimize first in each system iteration changed the behavior of the system. The system optimization behavior was then analyzed to determine what the effect of each testing condition was on the performance metrics. The behavior was also compared to the specific problem characteristics such as types of constraints and objective functions. This analysis is presented in the results and discussion sections.
2.4.2 Simulation Results

Simulations were performed on a test suite of problems from Evolutionary Algorithms by Coello et al. as well as from the test suite provided in Deb, et al. [56]. Solution paths for Multi-Objective Problem 4 (MOP4) under the three test conditions are presented as they display behavior exhibited by many of the test problems. MOP4 was chosen as the display case for two reasons: 1) the number of iterations was relatively small and 2) the Pareto Frontier and solution space had the same order of magnitude. These characteristics make MOP4 easy to visualize.

Results from all of the test problems for Euclidean distance and number of iterations are shown in Figure 2-3 and Figure 2-4 respectively. The number of iterations was averaged over 50 random starting points. The Euclidean distance to the Pareto Frontier was normalized by the Euclidean distance between the Pareto maximum and minimum [82]. A value of zero would indicate a solution directly on the Pareto Frontier and a value of 100% would indicate a solution at the normalizing distance. In Figure 2-3 three of the problems have values above 100% of the normalizing factor, their values are displayed in text boxes to accommodate the spread in chart values. Solution paths from the same starting point for MOP4 under the different conditions are shown in the three figures below. The Pareto Frontier on each plot is shown as circles. Figure 2-5 shows the solution path for the no bias condition. Figure 2-6 shows the solution path in the static bias condition with $b = 1.3$. The final system design in the static bias case was at 10% of the normalized distance from the Pareto Frontier, while the no bias and decreasing bias cases ended on the Pareto Frontier. Figure 2-7 shows the solution path in the decreasing bias case.

2.5 Discussion

Several themes emerge from analysis of the results presented above. First, the interview data clearly demonstrates the use of biases and in particular decreasing bias over time between subsystems in the organization studied. All of the negotiation structures in the organization, both formal and informal, are susceptible to this type
of error. The framework used in the simulations is derived from this information. Second, the use of biases leads to both sub-optimal and increased number of iterations in simulations. Third, this behavior was observed across a variety of multi-objective problem types and structures.

The use of a decreasing bias strategy was described by almost all of the subsystem engineers and also by the system integrators as a possible cause of system sub-optimality. In practice, subsystem engineers report that they provide conservative worst-case estimates of design parameter and point design information in discussions with other subsystems. Interviews indicated that this was due to a desire to "under-promise and over-deliver." It may have also be driven by a competition for resources such as personnel and money between the different subsystems. Decreasing biases is one strategy for ensuring the sub-system has the resources it needs to complete the required tasks and be robust to unexpected design constraints.

This can be an effective strategy at the subsystem level, but the simulations
Figure 2-4: Average number of system iterations for all three test conditions

demonstrated that it may lead to system-level issues. For example, Figure 2-5 shows the final system design to be directly on the Pareto Frontier. In Figure 2-6, the final system design found using the static bias strategy from the same starting point is further away from the Pareto Frontier and clearly less optimal. The decreasing bias condition shown in Figure 2-7 did not lead to sub-optimal results but did take more iterations. Although commonly used to compare optimization algorithms, the number of iterations is also an important metric when considering the design process. An increased number of iterations reflects a longer overall design process and time is an important resource in any design project. For example, time constraints can be viewed as constraining a design team to a fixed number of design iterations. A team using the decreasing bias strategy may reach a less optimal result given the same number of iterations when compared to a team using no biases, especially if the number of iterations required to reach the Pareto Frontier is large. However, given an infinite amount of time and other resources, the decreasing bias strategy actually
may be preferable to the no bias case because it reaches the same level of optimality and the "refinement" period near the end gives the design team more confidence that they are still in the feasible region.

The system response to the test conditions demonstrated in MOP4 was similar across many of the test suite problems tested. Figure 2-3 shows how in most of the problems the static bias condition was less optimal than the no bias and decreasing bias conditions. In the two problems which do not fit this pattern, MOP6 and DTLZ7, the structure of the problem caused the optimization algorithm to find the edge of the design space in a single iteration. The boundary of the design space was also on the Pareto Frontier. Thus all conditions found this point and the optimality of the final system design of these problems was insensitive to changes in the bias.

The system response demonstrated in MOP4 was also similar to many of the other test problems with respect to the number of iterations needed to reach a stopping condition. The number of iterations needed in the decreasing bias case was also higher.
than in the other two cases for most of the test problems. Problems whose objective functions were conic, such as MOP5, MOP7, MOPC1, and MOPC3, the behavior was more sporadic. Although it is unclear exactly how the conic structure caused the differences in behavior, the optimization algorithms used many iterations refining the final system design near the Pareto Frontier in the overlap of the two conic sections. The relative size of the static bias to the size of the overlap may have produced a stopping condition either before reaching this refinement stage, such as in MOP5, or kept it in the refinement stage longer as in MOP7, MOPC1, and MOPC3.

In practice, subsystem engineers also reported that sub-optimal irreversible design decisions were made early in the design process based on biased information from other subsystems. For example, a complicated and expensive structure may be designed and integrated into many subsystems based on mass constraints that are reported early on. The scale of the effect is due not only to the highly-connected nature of the subsystems but also the non-linear nature of the subsystem response to design
inputs. Small changes in inputs can have large effects on performance and cost.

This study was limited by several factors. The simulations were performed over a large number of problem types in the two test suites used. However, test suite problems do not necessarily accurately represent algorithm behavior in real-world problems. As such it is difficult to determine what the exact meaning of the increase in the distance from the Pareto Frontier or the increase in the number of iterations. However, this simulation does reflect insights provided by the interviewees. This study also only describes behavior reported by members of one organization. The information may not be representative of all design teams working on engineering complex systems.

Finally, this study presents results of a simplified two-player system. Since the two-player case shows that biased information affects the quality of design outcome, it could be argued that biased information passing in a multi-player system would also have adverse affects on design outcome. However, since the information passing
model developed in this study cannot be directly adapted to a multi-player system, these results may not indicate trends in simulations of larger systems. The sub-optimal system-level results reported in the interviews may not be directly or wholly due to biased information passing. The two-player system behavior is an initial step in expanding the concept of information biasing to larger systems. For a multi-agent system, a more complex model would need to be developed. The team structure, or how and in what order the subsystems communicate the biased information, would need to be defined. The majority of problems in the test suite used in this study can be easily extended to a multi-agent system. In addition, there may be issues of computational complexity or time with very large multi-agent systems.

2.6 Conclusions

Results demonstrated use of biased information passing throughout the organization studied at the subsystem level. This reportedly led to sub-optimal system-level results. Simulations of three conditions: no bias, fixed bias and decreasing bias showed significant changes in system behavior with the addition of biases. Two types of errors were observed regarding speed and optimality.

1. What strategies do real-world aerospace designers and engineers use when negotiating about design parameters with other sub-systems?

Practitioners interviewed reported using both MDO and Game Theoretic structures for negotiating trade-offs between sub-systems. Lower-level negotiations were done informally in a Game Theoretic structure, while higher-level negotiations were done formally in front of upper management committees. Interviewees also reported the use of biased information passing between sub-systems during negotiations at all levels.

2. What impact might these strategies have on system-level optimality?
Although the size of the effect was problem-dependent, biased information passing negatively affected system-level optimality across all problem types tested. Solutions that resulted from strategies incorporating fixed biased information passing negatively affected system-level optimality to a high degree. Solutions resulting from strategies incorporating a decreasing bias had the same level of optimality as those with no bias.

3. What impact might these strategies have on the speed of optimization?

The speed as measured by number of system iterations was not affected by the use of a fixed bias in most test problems. However, a decreasing bias strategy increased the number of iterations significantly and the amount increased for more complex problem types.
Chapter 3

Design for Micro-Enterprise

The theme of this thesis is about system-level design approaches. The previous chapter discussed investigating sub-system integration in large-scale, complex engineering problems. Another domain in which system-level design issues are highly relevant is the development of products for emerging markets.

Recent literature has focused on strategies for product growth opportunities in emerging markets [3, 4, 5]. This chapter examines product development for these markets as creating a product within a complex socio-technical system. A designer working in this area must balance the competing needs of many stakeholders, from the design firm and manufacturer to the end-user, from the local government to the many other participants in the supply chain. These competing objectives can be hard to determine across geographic and cultural boundaries. This chapter seeks to better understand how practitioners are currently balancing these competing objectives and what strategies may lead to more success in these markets. This chapter consists of two sections. In the first, a set of guidelines for performing these tasks, Design for Micro-Enterprise, is proposed based on interviews with practitioners and case studies of successful products in emerging markets. In the second section, the framework of design for micro-enterprise is refined through interviews with micro-entrepreneurs based in East Africa. The product attributes which affect purchasing decisions for these entrepreneurs are investigated and used to suggest improvements to the guidelines presented in the first section.
This chapter seeks to answer the following questions:

1. How are designers currently approaching product design for emerging markets?

2. What factors influence product success in these markets?

3. How can designers improve their approach to product design for these users?

3.1 Motivation

Emerging markets have historically been under-served in terms of products designed specifically for them. However, recent trends have seen many organizations, including NGOs, MNCs, and social enterprises begin to develop products for these markets [60, 83]. These organizations have been chiefly concerned with finding new strategies for delivering consumer goods and services to users in these markets. For example, many MNCs are currently using a "single-serve" distribution model where goods are packaged in small quantities for cash-constrained consumers [60, 84]. The increase in product development has been reflected by increased research in design methodologies, such as those described in Chapter 1. Even with the increased focus on these markets, there is a dearth of successful products.

Product failures can be attributed to many factors, but design literature points to a fundamental misunderstanding of the users [3, 9]. For example, Kellogg's attempted to introduce breakfast cereal to the rural Indian market, assuming that Indian consumers would use cold milk. It failed to anticipate the breakdown of user experience when the cereal was eaten with warm milk [?]. Another failure mode is a misjudgment of the balance between affordability and quality. Many consumers in these markets are extremely price-conscious due to limited finances, but have been shown to pay more for a quality product than risk financial loss due to product failure [59]. The use of a "global" platform or product designed without regard to local market needs is another common failure mode. Whirlpool's world washer, a single washing-machine platform meant for all emerging markets, did well in many markets, but failed in
India because the tolerances between the rotating drum and the case destroyed the thin layers of cloth common in Indian clothing [9].

Recent business literature suggests meeting unmet needs among micro-entrepreneurs, who represent a large segment of the population, may be the best strategy for operating in these markets [85, 86]. Micro-entrepreneurs are individuals who generate small amounts of income from their own business activities, often in an informal market sector [87]. Karnani estimates there may be limited profit potential among consumers in emerging markets due to the cost of reaching heterogenous and distributed customers and their low to nonexistent discretionary income [84]. London highlights how a focus on micro-entrepreneurs can create a positive value feedback loop between an organization and the entrepreneur and lead to more sustainable development [87]. The organization's product empowers the entrepreneur to generate more revenue and in turn, buy more products from the organization. In this vein, London further investigates the constraints facing BoP producers and how different ventures addressed these constraints [87]. Pitta provides an overview of the main threads in this discussion as well as case studies supporting this strategy [6]. This literature, as well as the observations and analyses of the case studies presented in this paper, demonstrate an important unmet user need for products among micro-entrepreneurs in emerging markets.

This chapter proposes a set of guidelines called Design for Micro-enterprise (DfME) and seeks to respond to many of these criticisms by linking observations from successful products with insights from business literature. In design methodology literature, each structured method has an overarching principle and perspective which informs design decisions. The above-mentioned strategies share a target market and the goal of alleviating global poverty. A gap in the design methodology literature is that these strategies view the user as a passive consumer. DfME is framed around the customer being a micro-entrepreneur. This means the designer needs to examine the requirements of both the micro-entrepreneur and his/her customers. The process therefore transforms from a traditional Business to Consumer (B2C) transaction to a Business-to-Business (B2B) transaction; from a consumer product to a commercial
product [88]. While this transition limits the type of products that can be designed, it helps address many of the obstacles facing designers in this field by focusing the design process on building a long-term relationship with the user and supporting their income generation. The approach presented in this section is meant to help the designer evaluate design ideas with this perspective in mind.

A unique distinction of B2B markets is that the relationship between the two enterprises is paramount. Every transaction is aimed at maintaining and improving this relationship; thereby growing the manufacturer's brand. In that vein, literature has shown that service contracts and guarantees become increasingly important in a commercial product [65]. Quality control has also been shown to be important for B2B and brand management [63]. Educating and interfacing with the enterprise client in an effective way when explaining the value proposition is another requirement for strong brand growth [65]. These factors contribute to establishing a strong positive brand identity in the market. Another insight from the business literature is to focus on income generation. Can the product generate revenue for the micro-entrepreneur? Dowling notes that B2B relationships "are designed on the understanding that each party contributes to the commercial success of the other [89]." This is especially important for micro-entrepreneurs whose resources are tightly constrained [60, 83].

DfME incorporates these insights with lessons drawn from the four case studies presented in this thesis to formulate a single approach. The guiding philosophy is to build brand identity by designing a product that increases the income of the micro-entrepreneur and supports a service plan that continues and grows the relationship between the micro-entrepreneur and the company.

3.2 Methodology

This section consists of two parts. First, insights from literature and interviews with four professional designers who work specifically designing goods for emerging markets are synthesized to present a framework for successful product design in these areas. These designers were selected because of their work developing products which are
currently being sold in emerging markets. Their job positions ranged from system-level designer to lead designer. The companies they represent included both small start-ups and large multi-national organizations. Second, the framework is explored against four case studies. The cases were selected along two criteria. The products had to have documented success in emerging markets and be at least partially used by micro-entreprises. The case studies represent a variety of product types, markets and company profiles and include some products and systems traditionally thought of for an individual user rather than for micro-enterprise (income generating for the consumer). The report uses the case study method described by Yin [90].

The goal of each case study is to gain insight into the strategies used by designers of successful products for emerging markets and use this to revise the framework. The four cases presented are the Nokia line of cell phones for emerging markets, a range of solar lamp products, several drip irrigation systems from India and two improved cookstove solutions. In each case study, the market for the product is analyzed. Contextual information about the product and manufacturer is also presented. Although performance metrics such as sales numbers were examined, it is difficult to gain independent confirmation of the numbers represented by the organizations themselves [10]. Instead, our analyses of these companies focused on whether the products were successfully sold on the market and which DfME guidelines, if any, were met. Metrics such as size of the company, type of company, location, and company age are presented to give a more complete picture of the product development environment. Product features are then compared to the DfME framework. Two alternative strategies for product success, Design for Cost and Identifying a good business opportunity, are examined with respect to each case. These two alternative strategies were applied because they were commonly used in emerging markets and they contrast with DfME in focus. We expect these alternatives to highlight DfME’s strengths and shortcomings. Finally, design strategies drawn from the case examples are summarized.

The final DfME guidelines, which synthesize business insights and designer insights and also include lessons learned from the case studies, are then presented. These are
meant to be used by future designers as one approach when considering products of this type for emerging markets.

3.3 Design for Micro-enterprise

The interviews with the four practitioners highlighted strategies that they believed were important to consider when designing products for emerging markets. The main conclusion from the interviews was that the design choices should support the business plan of the end-user. As one designer noted, "income is the best 'hook' for a product," meaning customers are most likely to buy products they can see will help them generate income. DfME is a specific application of user-centric design where the user is a micro-entrepreneur in an emerging market. The guidelines are a synthesis of the insights shared by the practitioners in the interviews. The guidelines are all within the context of gaining a deep understanding of the users needs. The guidelines are meant to focus the designer's questions and strategies around the complex challenges facing these users. In the case studies the details of the products investigated will be compared to both these guidelines and to two other models for product success.

Guideline 1: Design for the Entrepreneur's Business Plan

The first and most important guideline is to design for the entrepreneur's business plan. Implicit in this guideline is that the designer must have a deep understanding of the needs of the user not only as a consumer but also as a micro-entrepreneur. Several strategies were described by the designers as ways to achieve this goal.

Revenue Generating: The first is to make revenue generation central to the functionality of the product. This revenue generation should be clear, easily explained and understood by the end-user. Is it clear how to make money using the product? For example, power metering in several solar systems currently on the market allows micro-grid operators to accurately charge their customers.

Upgradable: The second strategy is to design the product to accommodate different user needs as the business grows with time [91]. The product should have
the ability to increase its performance capacity as the entrepreneur's business and capital grow. Can you size the product appropriately for your business and then easily grow it later? For example, a farmer buying a drip irrigation system can buy a small system and then later buy add-ons to increase its capacity without buying a whole new system.

**Guideline 2: Establish a Reliable Brand Identity**

The second guideline revolves around establishing a positive brand identity associated with reliability. A positive service relationship is imperative to the relationship between the entrepreneur and manufacturer. The entrepreneur relies on the product and has a low tolerance for product failure [9]. The interviewed designers related two main strategies for avoiding product failure.

**Design for Reliability:** One method is to design a robust product with a long expected life-cycle which does not need to be serviced very often. This can be done through material selection, component selection and simplification of the system. A rich body of literature describes similar strategies under Design for Reliability [92].

**Design for Maintainability:** Another strategy is to design the product so it can be serviced locally. Organizations utilize methods such as standardized parts and easy to disassemble systems. Okogbaa and Otieno provide an excellent overview of other strategies in Design for Maintainability [26].

**Guideline 3: Consider Multi-functionality**

The final guideline is to consider multi-functional or convergence products [93]. Practitioners reported that the use of this strategy is highly dependent on the particular market and product type. For some markets and product types, such as solar lanterns, multi-functionality was seen as key to a product’s success. The solar lantern was more desirable to the consumer with the ability to charge cell phones [94]. However, multi-functionality can lead to performance trade-offs. A Swiss army knife has many blades but none cut as well as a single purpose-designed knife. This strategy would be much
less useful for agricultural processing products such as a wheat thresher. Despite this limitation, the existence of a number of counter-intuitive examples suggest that designers should consider if it is useful to the end-user to include additional functions in their product aside from the core functionality.

These guidelines are a combination of literature and insights gained from interviews with the four practitioners. They are meant to suggest which strategies or perspectives are most important when designing for emerging markets. In short, DfME suggests that income generation, serviceability and then multi-functionality are the key aspects, in that order, for product success in emerging markets. Although there are many alternative strategies, several of which are presented above, we will be comparing DfME to Design for Affordability which focuses on minimizing the retail price point of the product.

3.4 Results

Case Study 1: Nokia Emerging Market Cell Phones

The Nokia line of cell phones has been cited as an exemplar of successful product and business strategy in emerging markets, with approximately 35% of their total sales in 2009 coming from emerging markets [59]. Many phones in these markets are used by micro-entrepreneurs. These phone owners generally operate as a mobile pay phone, renting out their phone to others in the community to make calls when infrastructure lacks other communication means. Figure 3-1 shows the Nokia 1200, one of the most popular entry-level phones sold in emerging markets [95]. The dominance of the Nokia phone in these markets is a good example of how the guiding principles of Design for Micro-enterprise can be implemented. Although this case study will focus on the features and business innovations that impact micro-entrepreneurs, the design of the cell phones was within the context of user-centric design. Nokia invested heavily in understanding the local users' needs. They established design centers in the emerging markets they were targeting [9]. This effort allowed them to gain a
competitive advantage over both MNCs, such as Motorola, as well as local cell phone manufacturers. During the time period from 2005 to 2009, Motorola produced a line of phone with same price points as Nokia which fared poorly and led to Motorola falling to fourth in many of the emerging markets [59].

In designing their line of phones for emerging markets, Nokia focused on building a strong positive brand identity associated with reliability. In an interview Antti Kujala, the lead designer for entry-level phones, said Nokia wanted to “avoid the look of ‘cheaper’...boxes that look very brittle and lack robustness [95].” A dust-repellent keyboard, higher-quality materials and an easy-grip back designed for high-humidity environments are examples of design decisions driven by reliability concerns [95, 59]. One user interviewed explained that all of his family used Nokia phones because, “You can drop it on the ground many times and it still works [96].” The company also made servicing their phones easier by sharing components among different models and having fewer components than competing models [97]. Nokia also invested heavily in building a distribution and retail network which doubled as a service network. For example, it used a fleet of dedicated vans to reach rural Indian customers for both marketing and service work [97]. Nokia also invested in building relationships with independent retailers to further grow their distribution and service network [59]. In summary, Nokia maintained a strong brand identity in emerging markets. It produces a high-quality product that is reliable in local conditions, investing in local technicians and distributors as well as its own network when needed.

Nokia also utilized a multi-functional strategy with their phones. According to Kujala, the change in paradigm from a single-owner phone to a shared-use phone was pivotal in their design process [95]. The Nokia phones featured multiple contact lists which made it easy for users to share the same phone and keep their contact lists separate [9]. The phones were also equipped with a one-touch LED flashlight. The phones are also often equipped with a radio receiver. These features, especially the flashlight, are cited as a major advantage over competing models and a driving force behind Nokia’s No. 1 position at the time in emerging markets [59].

Nokia did an excellent job of educating potential customers about their products
and how the phones can be used by micro-entrepreneurs. Nokia included 80 languages in its user interface, meaning in situations where there are multiple local languages any user can easily interact with the phone [9]. The phone featured a demo mode to familiarize the user with the operation of the phone. Nokia also developed “eRefills”, a prepaid usage tracker which displays the exact amount and price of the airtime used in each call [59]. This metering was useful when charging customers per call. The multiple address books are also useful for the entrepreneur as a service provided to repeat customers. Without this business model, many of Nokia’s users in emerging markets would not have been able to afford the phone [59].

Although Nokia made efforts to reduce the retail cost of the phone, many of their design decisions suggest that they were not making the cheapest possible phone. These decisions include their material choice, the effort to avoid a cheaper look, and the final cost which was a significant portion of their target market’s income. In this case, another compelling alternative is that mobile phones are simply so useful in these markets, the demand for the ability to communicate is so high, that these design decisions did not affect consumers’ choices. Customers would buy the phone regardless of the material selected or whether it supported their business. However, this theory does not explain why Nokia was so dominant compared to other cell phone providers.

Nokia was able to achieve and maintain its No. 1 position in emerging markets
from 2003 to 2010 by utilizing an understanding of their customers, supporting micro-enterprise activities and by providing a high-quality phone with locally available service. One aspect not covered in the original formulation of the DfME guidelines is the importance of educating the end-user on how the product can support their business. This will be incorporated into the following case studies.

**Case Study 2: Solar Lighting Technology**

According to a joint International Finance Corporation and World Bank report, 590 million people are not connected to their national electrical grid in Africa alone. Many users rely on flame-based technologies, such as paraffin lamps, for lighting [94]. Driven by this large potential market, solar lighting technology has become a rapidly growing field for emerging markets. Companies such as D. Light Design and Greenlight Planet have produced solar lighting solutions aimed at this market. Their user base includes many entrepreneurs who either use the lights to support their business; keeping their shop open later at night, advertising their shop or using the lights to charge cellphones for a fee [94]. Although these companies utilized different strategies, their shared goal was to provide reliable lighting in off-grid situations. Many other companies have also focused on using solar technology for electricity generation in these markets. Although these technologies can also be considered solar lighting solutions, this case study will focus solely on products whose primary focus is lighting; specifically those shown in Figure 3-2, the D.light S10 and the Greenlight Planet Sun King Pro [98, 99].

This case study will highlight issues which came up repeatedly in the two interviews with designers working on solar lighting products. The first is the durability of the product and how it relates to product branding and customer acceptance. The second is the desire for multi-purpose functionality in the lighting solution, especially as it applies to entrepreneurs. The third is the importance of educating the consumer about the value proposition and embedding that in the functionality of the product. Finally, the issue of affordability is addressed.

Product reliability was highlighted as a foremost concern in both designer interviews and market research. Lighting Africa found that "lack of trust in product
quality and credibility of manufacturer’s claims" were major deterrents for potential customers. Customers interviewed were highly risk-averse to product failure [94]. Designers mitigated concern about product failure through a focus on durability and longevity. This was demonstrated in several ways including feature selection, marketing and service networks. The material and feature selection of many products offered in this area focus on durability. The technical specifications for all of the products highlighted their resistance to breaking. For example, the Sun King Pro lamp offers “unbeatable solar panel durability" with a strengthened glass panel face [99]. The d.light S10 features rain-resistant housings [98]. Long product life cycles are also emphasized. The Sun King highlights its expected battery life of 5 years [99]. The S10 has “robust circuitry for long-life performance [98].” Several of the products also feature active battery protection to prevent deep discharging and overcharging. These features enhance battery life. Another strategy was to focus on the serviceability of the product. The S10 has an easily replaceable battery. The Sun King has a repairable junction box. Several of the products have a 1-year product warranty for the end-user.

Users also preferred having a multi-functional product. The Lighting Africa survey respondents strongly preferred multi-purpose lighting solutions because they “only have one or two lighting devices but more places to light [94]." Micro-entrepreneurs interviewed had a marked preference for multi-functional lighting products. They de-
sired many more lit locations than other respondents, including the till, storerooms, product shelves and storefront. Companies responded by incorporating several different use cases into their product. All of the products analyzed here feature handles which function as stands and hooks for different lighting needs. The products can be used and are marketed as task lighting, flashlights for mobile lighting, and lanterns/lamps for indoor lighting. The Sun King also charges cell phones. This was seen by designers in different markets in a variety of ways. Some users rented out the cell phone charging feature to generate income. In other markets, cell phone charging was reported as being used as a convergence product by single users. One company which started out pursuing a solar lantern design switched to simply solar charging as users highly valued this feature.

The Lighting Africa report concluded that “educating the consumer is very important. ...[Companies] must make buyers aware of the problems that they are facing and how the new lighting devices overcome [them] [94].” The report emphasizes teaching users about savings in operating costs, ancillary benefits to education and the impact on escaping poverty. This is especially true for micro-entrepreneurs, who spent more on lighting than the average user [94]. One educational strategy was to focus marketing on savings gained by switching from kerosene or paraffin to solar energy. All of the products mentioned this is their promotional literature. Another strategy was to make the devices very easy to use and thereby eliminate the need to explain how the product solves the user’s needs. All three devices have minimal connectors, one for connecting to the solar panel and possibly another for charging phones, and simple on-off switches and brightness controls. The Sun King Pro addressed this issue using feedback monitoring systems. The Sun King has an LCD display the amount of operating time left in the battery and also a charging indicator for help placing the solar panel.

Finally, the issue of affordability is a major concern in emerging markets. Although some strategies emphasize lowering the price point as much as possible, both designers and the Lighting Africa report highlighted that lowering the price point should not be done at the expense of durability or performance. The willingness to pay for solar
lanterns increased five to ten times between hearing the initial idea of a product and holding the physical product [94]. "Consumers . . . quickly recognize and respond to the value proposition [solar lights] present once they have more information [94]."

The products range from $15-25, a large portion of the average $125 monthly income for a family of four in the Lighting Africa survey. These companies have found success at these relatively high price points by offering quality durable products and focusing on brand management. For example, d. light had sold over 220,000 units by the end of 2010. This is encapsulated in user responses to what constitutes an ideal lighting product. Respondents indicated that the ideal lighting product "should be made by a reputable manufacturer in order to increase consumer confidence . . . indicating the value of building up brand recognition. [94]"

An affordable price point is, as demonstrated above, a critical part of the success of any solar lamp. However, the market research shows that these lamps are finding success at a relatively high price point. It is possible that any solar light would be successful in this area due to high demand. However, many solar solutions are not successful and kerosene lamps continue to dominate the market. The lamps covered in this study have been able to overcome the familiarity and popularity of kerosene lamps by focusing on income benefits and adding multifunctional elements such as phone charging. Also many companies offer cheaper alternatives, including the lower end of the product family from d.light. The relative success of the models which include phone charging, use more robust materials and have better performance does not fit the Design for Cost model.

Companies and designers in the rapidly growing solar lighting market have utilized strategies focusing on the durability, reliability and multi-purpose aspects of their products. Several for-profit start-ups have found considerable success in this space by emphasizing the value proposition in their product and empowering micro-entrepreneurs to make income using their product.
Case Study 3: Drip irrigation in India

Drip irrigation is the practice of delivering small amounts of water directly to the base of each plant in a field using a system of tubes with small emitters at each plant location. Originally developed for large-scale agriculture in arid climates such as Israel, it has recently been the focus of many small-scale farmers in emerging markets [100]. These systems have many advantages over other irrigation schemes, especially in areas where water management is a crucial issue. Drip irrigation has grown rapidly in India, driven by both government programs aimed at improving water use efficiency and by the increases in crop yield using this method [101]. There are a variety of organizations who have developed products for this market. Large domestic corporations such as Jain Irrigation Ltd, MNCs such as John Deere and Netafim, non-profits such as International Development Enterprises India (IDEI), and small start-ups such as Driptech are all targeting small farmers in this area. These companies are seeing explosive growth in these product areas. For example, Jain Irrigation Ltd.’s revenue from micro-irrigation products has quadrupled from 2007-2011 and accounts for over half of its total revenue [102]. One notable aspect of this trend is the treatment of the farmer as a micro-entrepreneur. The irrigation systems are often marketed as a way of growing out-of-season crops and thereby positively affecting the bottom line of the farmer [?]. This case study will examine several of these products, specifically the Jain micro-irrigation range of products (shown in Figure 3-3), the IDEI KB drip system and the Driptech irrigation system. Interviews with designers regarding the strategies they used as well as market research regarding the impact of drip irrigation for small farmers will also be examined.

The choice to focus on drip irrigation instead of other types of irrigation schemes, such as flood or sprinkler irrigation, was a major decision for many of the organizations in this area. This was highlighted in reports and the interview with a designer who led the development of a drip irrigation product for India. Several reasons were given for choosing drip irrigation, but the driving force was the total amount of income gained by using drip irrigation. As seen in Indian field tests on a variety of crops,
drip irrigation has a positive impact on both crop yield and water savings [100, 101]. Depending on the crop, the increase in yield is anywhere from 5-50% with most yields increasing 30% using 50-60% less water. The ability to use these systems without access to electricity was another factor. Other systems require electric or diesel pumps that have larger operating costs. Drip irrigation technology was chosen due to its impact on the small-scale farmer’s bottom line.

These systems support the entrepreneur’s business in other ways as well. All of the systems are designed to be modular and expandable. The farmer can easily buy an appropriately sized system, adding more tubes for larger plots of land. In this way the farmer can also add capacity in the future when they have more capital without losing the original investment. The farmer can easily optimize the irrigation system for their farm. Other strategies include service networks that provide services outside of the irrigation system. For example, Jain Irrigation Ltd. provides both business and agricultural support free of charge to make sure that their systems have the greatest possible economic impact on their customers. IDEI collects market information on local high value crops and does cost-benefit analyses for their customers. They further support the farmers by identifying and enabling some local farmers to become nursery growers and micro-entrepreneurs selling sustainable farming materials to their community.

Serviceability was another concern brought up by the designer. The products
addressed this issue in different ways. Driptech explicitly designed their system with fewer pieces, making it easier to maintain. Their system also replaced emitters located at the plant with precisely placed holes in the tubing. This choice reduces the amount of skill and tools needed to repair the system, allowing the farmer to perform the most common repairs. The Jain micro-irrigation system is more complex, but has a large local sales and service network. The design of their system focused on reliability. The system has filters and other mechanisms to prevent clogging of the emitters and increase the lifetime of the product. This also leads to a more uniform distribution of water.

IDEI chose a hybrid strategy with the KB drip system. It is designed to be highly customizable. The farmer can choose to use pre-punched holes, micro-tubes or button emitters as the water emitting device. The system can be operated using gravity or with a motor, diesel or electric. These choices represent a trade-off between performance, complexity and cost. A farmer can easily switch to a more complex system if the need arises. IDEI also has a large system of local traders they use for sales and service. They utilize the network of local micro-entrepreneurs they created to keep in contact with their users and get feedback.

Many irrigation systems focus on achieving the lowest possible cost due to the small margins involved in small-scale agricultural production. However, the systems presented chose more expensive solutions, such as complex emitters, because of increased income benefits for the farmer. As there are many irrigation options open to each farmer depending on their situation, it is unlikely that the increase in use of these systems is due to a major unmet demand specifically for drip irrigation. Rather, the features of drip irrigation which help the farmer’s business

In conclusion, irrigation companies in India have achieved rapid growth through drip irrigations products and support services which focus on improving the revenue of small-holder farmers.
Case study 4: Improved Cookstoves

This case study compares two improved cookstoves, shown in Figure 3-4: the Protos Plant Oil Stove by Bosch and Siemens Home Appliances Group (BSH) and the Grameen Shakti Improved Cooking Stove (ICS). Grameen Shakti is a local NGO in Bangladesh which focuses on developing micro-entrepreneurs through technology. The Bosch and Siemens Home Appliances group is a MNC which was targeting rural consumers in Indonesia with the Protos. Although they were operating in different markets, both organizations' stated goal was to combat indoor air pollution caused by cooking on traditional stoves or open fires [103, 104]. This is a driving force in the development of many improved cookstoves as indoor air pollution causes upwards of 1.5 million deaths per year, mainly in emerging markets [105].

The Protos illustrates how consumer design goals can lead to sub-optimal outcomes. BSH stated that the goal in developing the Protos was to create a stove which was "high quality, safe and as easy as possible to use [104]." However the device also had to be "cheap enough for people in developing countries to be able to afford it [104]." This exemplifies common thinking during consumer product development, the tradeoff between quality and price matched as close as possible to consumer needs, but without a clear understanding of the consumer's broader potential need for micro-enterprise. The product was tightly focused on cooking in the home, and therefore was not multi-functional. The design did not account for a local service
network or have features intended to make it more robust. This was later identified by BSH as the most important factor in its lack of success. The Protos went through several field trials and was in series production in Indonesia before being discontinued due to lack of sales. BSH determined that the lack of an established market for plant oil and the increased time and effort to cook when compared to kerosene stoves were the two main factors in its lack of success.

The Grameen Shakti ICS took a different approach in its design. Grameen Shakti developed the ICS for use by micro-entrepreneurs such as restaurants and food production such as bakeries, in addition to consumer home use [103]. The product met all of the strategies listed in the guidelines. The stove is upgradable and available in several different sizes, from one to three mouth openings [103]. The ICS is also designed for service with much of the ICS manufacturing and repair occurring at a local level. The metal chimney and grates are manufactured at one of 45 Grameen Technology Centers and then the stoves are assembled and built locally. Grameen Shakti achieves this through a sales and service network they developed including 3,500 community technicians and entrepreneurs. This network acts in conjunction with Grameen’s extensive network of 1400 local offices tasked with linking the technology with income-generating activities. The ICS is also multi-functional with optional add-ons for soap manufacturing [103]. The ICS has been successful in this market with 391,000 units sold and installed since 2006 [106].

As this case study presents, the Grameen Shakti ICS was able to find success in the same product area as the Protos by focusing on supporting entrepreneurs and local service. BSH was unsuccessful despite the effort and resources spent on testing and developing the Protos stove. There are major differences between the two projects that may have contributed to the difference in success. First, Grameen Shakti, as a local NGO, may have a better understanding of user needs than BSH. Second, differences in the markets may have contributed to the results. It is possible that for structural reasons rural Bangladesh may be a better market opportunity than rural Indonesia. Finally, the distribution and service network developed by Grameen Shakti certainly were a large factor in its acceptance by end-users. However, this
highlights the differences in the designs. The ICS was set up to take advantage of the local network and the Protos was not designed to be serviced by local technicians. It is unclear whether the local technicians had the knowledge or tools necessary to effectively repair the Protos stoves.

3.5 Discussion

This chapter proposes a new set of guidelines focused on developing commercial products for micro-entrepreneurs in emerging markets. The guidelines were drawn from interviews with four practicing designers and a literature analysis. These guidelines form a model for how product success can be achieved in these markets. This model emphasizes a focus on the entrepreneur's business plan, the relationship between the manufacturer and the micro-entrepreneur and multi-functionality over other factors. Several themes emerged from case studies. First, the guidelines are presented in order of importance. Revenue generation for the micro-entrepreneur was central to the product's success in all of the case studies. For example, in the drip irrigation case study, Jain Irrigation provided extra services free of charge to ensure their product generated additional income for their users. Although the case studies also highlighted how multi-functionality can have a positive effect on product success, its importance was highly dependent on the market. For example, in the cell phone and lighting case studies users placed a large premium on multi-functionality, but did not in the other examples. Second, educating the consumer about the value proposition was considered integral to product success. Companies in these case studies provided features or services that explained to potential customers how to generate revenue with their product. This was not explicitly indicated in the original formulation of the guidelines. Finally, alternative models for product success, such as Design for Cost and product success due to a large unmet demand did not fit these case studies well.

Although these alternative strategies are compelling in many ways, they were not appropriate for these cases. An affordable retail price is essential to product success in many markets. Lowering the price is one way to increase the value propo-
sition of a product. However, the results from the case studies suggest that other factors are more important to product success, especially when designing for micro-entrepreneurs. All of the examples were able to achieve success at relatively high price points in the face of cheaper competitors. Identifying a good business opportunity is also critical to product success. If there is a high demand for your type of product, then this may outweigh other factors which affect product success. For example, if there is a high demand for mobile communication in a particular market, any cell phone might become successful regardless of design intent. This does not fit the examples presented above as similar products were not successful in the same markets.

As shown in Table 3.1, the case studies represent a wide range of organizations and products. Small, medium and large companies have all used the strategies presented to achieve success in these areas. These comparisons are meant to highlight the range of companies working in this area and give a sense of the context for the case studies, not to draw conclusions about which product is the most successful.

<table>
<thead>
<tr>
<th>Product</th>
<th>Org. Type</th>
<th>Org. Age</th>
<th>No. Employees</th>
<th>Location</th>
<th>Unit Sales</th>
<th>Price ($)</th>
<th>Time on Market (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nokia 1100</td>
<td>MNC</td>
<td>148</td>
<td>100000</td>
<td>Global</td>
<td>250 Million</td>
<td>90</td>
<td>9</td>
</tr>
<tr>
<td>D.Light S10</td>
<td>SME</td>
<td>6</td>
<td>100</td>
<td>43 Countries</td>
<td>1.3 Million</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>Sun King Pro</td>
<td>SME</td>
<td>5</td>
<td>30</td>
<td>India, Africa</td>
<td>3.5 Million Users</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>Driptech</td>
<td>SME</td>
<td>5</td>
<td>30</td>
<td>India</td>
<td>&gt;10000</td>
<td>185/acre</td>
<td>4</td>
</tr>
<tr>
<td>IDEI KB Drip</td>
<td>NGO</td>
<td>12</td>
<td>185</td>
<td>India</td>
<td>&gt;250000</td>
<td>148/acre</td>
<td>12</td>
</tr>
<tr>
<td>Jain</td>
<td>MNC</td>
<td>50</td>
<td>7500</td>
<td>India</td>
<td>&gt;500000</td>
<td>370/acre</td>
<td>18</td>
</tr>
<tr>
<td>BS&amp;H Protos</td>
<td>MNC</td>
<td>46</td>
<td>46000</td>
<td>Indonesia</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Grameen ICS</td>
<td>SME</td>
<td>1500</td>
<td>7500</td>
<td>Bangladesh</td>
<td>632000</td>
<td>10</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 3.1: Case Study Comparison
This study is limited by several factors. First, although the case studies presented represent a variety of markets and product types, the set is not exhaustive and may contain selection biases or errors. This is also true of the sales performance data, which was compiled from a variety of sources and represented a conservative lower bound of the number of units sold. Also, because the products have been on the market for differing lengths of time, this may be under-representing the success of newer products. Likewise, for many of the products there was no independent testing of the features or specifications listed by the manufacturers. Although these data existed and were used for the lighting products, the rest of the products were categorized primarily on the manufacturers' claims. Finally, a comparison of units sold across product categories is limited due to differences between product types. For example, a nutritional bar will have a much higher sales volume than an automobile for the same market. A better metric might be economic impact on the entrepreneur, but that type of data is difficult to determine.

3.6 Conclusion

In conclusion, this section proposes a new approach for product design for emerging markets called Design for Micro-scale Enterprise. This approach consists of three guidelines: Design for the Entrepreneur's Business Plan, Establish a Reliable Brand Identity and Consider Multi-functionality. These guideline were achieved through strategies such as design for reliability, design for maintainability, upgradeability and multi-functionality. As seen in the case studies, considerable success can be achieved in these markets by focusing on the unmet needs of micro-entrepreneurs.
Chapter 4

Field Study: Micro-entrepreneur Purchasing Decisions

The previous chapter outlined a framework for product success in emerging markets that focused on micro-entrepreneurs. This model was based on interviews with practitioners, literature reviews and case studies. The factors identified as key to product success when designing for micro-entrepreneurs were revenue generation, reliability and multi-functionality with revenue generation and reliability being the most important. In essence, the framework states that micro-entrepreneurs in these markets will buy a product if they believe it will make them money and will not fail in the short term. In order to further refine this framework and gain a better understanding of factors which affect product success in these situations, interviews were carried out with micro-entrepreneurs in East Africa. This section presents the results from these interviews and implications for the DfME guidelines.

4.1 Motivation

This chapter extends the previous section on a framework for design for emerging markets. The interviewed designers and case studies point to a need to understand the requirements of micro-entrepreneurs in these markets. They suggest that focusing on these users as well as the end-users may be a pathway to product success.
This section works to refine the DfME framework by identifying the product evaluation strategies of micro-entrepreneurs in these markets. By better understanding the product purchasing decisions of micro-entrepreneurs it may be possible to improve the approach to product development in these markets. The work seeks to examine which product attributes affect the purchasing decisions and which of these factors is the most important.

The guidelines posited that reliability, revenue generation and multi-functionality were the key factors to product purchasing decisions of micro-entrepreneurs in emerging markets. To test these hypotheses regarding product attributes, a research collaboration with a social enterprise in East Africa was established. The company produces and sells public toilet franchises in the slum areas of a capital city in East Africa. Micro-entrepreneurs then charge the public for use of the toilets. The branded toilets compete with other pay-for-use public toilets and are intended to have a better user experience and be more sanitary than the competition. The parent company sells the toilets to the micro-entrepreneurs at near-cost levels and collects the waste, which is turned into fertilizer and other products. A key reason for choosing this company for a research collaboration was their focus on micro-entrepreneurs as their customers instead of end-users. The company focused on micro-entrepreneurs because they thought the alignment of incentives would be a more sustainable business model. At the time of the study in April 2014, the company had existed for four years and had sold approximately 400 toilets in the slum area. They were working with approximately 150 micro-entrepreneurs running the franchises.

The public toilet franchises compete in their neighborhood with existing pay-for-use pit latrine toilets. The major differences between the franchises and their competition is the cleanliness of the toilet, the user experience using the toilet and the treatment of the waste. The toilets used by the franchises are built with concrete walls instead of corrugated steel and have tile floors allowing them to be cleaned more easily. The franchise agreement requires the franchisee to provide toilet paper to the customer, place sawdust on the floor to absorb moisture, and offer soap and water. The agreement also requires the franchisee to clean the toilet frequently. This
agreement structure creates a better user experience for the end-user. Finally, the waste is collected every day by the parent company to be processed into fertilizer. This also contributes to the cleanliness of the toilet.

The research collaboration was motivated mainly by the need to explore purchasing decisions of micro-entrepreneurs in an emerging market. These particular franchisees were a notable case because of some non-intuitive behavior which was observed by the parent company. The franchise agreement requires the franchisee to purchase soap and toilet paper. The main company offers "high-quality" toilet paper and soap brands at wholesale prices to their franchisees in an attempt to improve and standardize the end-user experience of their brand. Only 17% of the franchisees buy the toilet paper and 30% buy the soap. These are low purchase rates for a "better" product being offered at the same price as the "lower-quality" alternative. This disconnect makes understanding their purchase decisions both important to the parent company but also interesting from a design standpoint.

Given this context, this chapter seeks to answer the following questions:

1. What factors affect a micro-entrepreneur's decision to buy a product?
2. Which product attributes contribute to the purchasing decision?
3. Which product attributes are the most important to the purchasing decision?

Specifically, this chapter seeks to test the following hypotheses.

h1: Product attributes are the most important factors to a micro-entrepreneur's purchasing decision. This is as opposed to macro-economic or demographic factors.

h2: Durability, reliability, amount of revenue generated, and multi-functionality contribute to the purchasing decision. This set notably does not include price.

h3: Revenue generated followed by reliability are the most important to the purchasing decision.
4.2 Methodology

This portion of the study consisted of two sets of interviews and collection of sales data and market research. Thirty-three micro-entrepreneurs who operate franchises of the public toilet franchise were interviewed at their franchise locations about their purchasing decisions. In some cases, employees of the micro-entrepreneur who ran the day-to-day operations and made purchasing decisions were interviewed. Secondly, six field officers of the parent company in charge of liaising with the micro-entrepreneurs were interviewed about purchasing strategies of the micro-entrepreneurs. Finally, market research and sales data were provided by the parent company.

4.2.1 Participant Selection

The parent company provides services to 143 franchisees distributed throughout several neighborhoods in slum area. These neighborhoods were labeled as area 1-7. Each field officer for the parent company is responsible for a different area. Interviews were conducted by randomly selecting a field officer to shadow on each day. The number of times each field officer was followed was weighted to provide coverage based on how many franchisees were in each area. For example, area 1 had the most franchisees with 70 franchises. Each franchisee on the field officer’s route was then interviewed. This corresponds with three to five interviews per day. Additionally, two franchisees considered by the parent company to be the most “entrepreneurial” were interviewed. Finally, all six field officers were interviewed about larger trends in their respective areas.

4.2.2 Interview Characteristics

The interviews consisted of approximately 20 minutes of questions regarding the purchasing decisions of the franchisees. Each open-ended interview started with informed consent. The subject was then asked “Which products are most important for the operation of your business?” This was followed by asking a series of questions about each product mentioned. The follow-up questions were meant to ascertain: 1) what
products of that type are available to the subject, 2) which product they currently buy, 3) what product attributes contribute to their preference for that particular product, and 4) which product attribute contributes the most to their preference. For example, one respondent said soap was important to the operation of the toilet. The follow-up questions determined that the local Sunlight, Ushindi, Panga and Jamaa brands of soap could be obtained by the subject at certain price points. The interviewee responded that they purchased Sunlight soap for use in their business because it had a pleasant scent and lasted longer than the other brands. Finally, the subject indicated that how long the soap lasted before needing to be replaced was the most important factor in their purchasing decision process.

Although the follow-up questions were asked about all of the products mentioned by each subject, at a minimum the subject was questioned about their purchasing decisions for soap, toilet paper, mops, and solar lanterns as these were the products necessitated in their franchise contracts. The questions were all posed in a relative fashion; “Why do you prefer this particular product to the other ones available to you?” “Please compare the Toilex toilet paper to Jumbo toilet paper, which one do you think will last longer?”

In the interviews with the field officers, the same questions were asked but about their areas in general. Additionally, the field officers were asked about general trends in sales in their areas and why they felt these trends existed. They were also asked about what differences existed at a macro level between their area and other areas.

4.2.3 Market Research

The parent company offers franchisees a selection of products essential to the operation of their toilets as well as a variety of add-ons that might improve business value such as promotional signs. A list of the products offered in the catalog are listed in Table 4.1. Sales data from this catalog was provided by the parent company. Additionally, the profitability of the franchisees interviewed and average profitability were also provided. Market research regarding which products are available to the franchisees was also collected.
Table 4.1: Upgrade Catalog

<table>
<thead>
<tr>
<th>Product</th>
<th>Price ($)</th>
<th>Product</th>
<th>Price ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bench</td>
<td>135.1</td>
<td>Sun King Pro</td>
<td>40.00</td>
</tr>
<tr>
<td>Privacy Barrier</td>
<td>49.2</td>
<td>Sun King Solo</td>
<td>16.00</td>
</tr>
<tr>
<td>Branding Paint Job</td>
<td>18.5</td>
<td>Air Freshener</td>
<td>2.00</td>
</tr>
<tr>
<td>Branded umbrella and chair</td>
<td>31.4</td>
<td>Branded Shirt</td>
<td>4.50</td>
</tr>
<tr>
<td>Small sign</td>
<td>1</td>
<td>Branded Apron</td>
<td>8.33</td>
</tr>
<tr>
<td>10 stickers</td>
<td>2.2</td>
<td>Branded Dust Coat</td>
<td>9.40</td>
</tr>
</tbody>
</table>

4.3 Results

The interviews began with the question, "what products are most important to the operation of your business?" The full list of responses included: soap, toilet paper, mop and bucket, disinfectant, air freshener, solar lantern, sawdust and hand towel. These responses reflected the core function of their business which was providing a clean toilet. However, out of that set only four were reported by a majority of the respondents: soap, toilet paper, a mop and solar lanterns. These four products will be the focus of the reported results.

4.3.1 Price Point vs. Cost Over Time

The subjects differed on how to approach product purchasing decisions, but one notable theme emerged from many of the interviews. In response to the question of why they preferred a given product to other options respondents said a variation on "cheap is expensive." Seven of the thirty-three respondents said it directly. Other variations included "cheapest is very expensive, costing you all the time," and "you know what they say, cheap is expensive." When asked to explain, respondents indicated that it was a general idiom that products with the lowest price point signaled lower quality and would actually cost you more over time. The lowest price point was not attractive to these buyers. It should be noted that two respondents did say they would buy the cheapest possible mop. This does suggest that the subjects were not concerned with the cost of the products, but that they were concerned with the cost over time, not the price point. These quotes illustrate that the entrepreneurs would avoid the lowest
price point in the market and focus on the cost over time.

4.3.2 Two Business Strategies

Given this definition of cost as cost over time rather than price point, an interesting result from the interviews is that the respondents can be broadly categorized into two strategies: cost-reducing and customer-centric. These groups are defined with respect to the entrepreneur’s strategy for increasing profit. A simplified calculation of profit would subtract the cost from the revenue. The cost-reducing group assumed that revenue was going to stay the same and tried to minimize cost over time in order to increase profit. The customer-centric group attempt to increase profit by increasing revenue through additional customers even if it meant increasing cost. This split in strategy can be understood as the micro-entrepreneur choosing which curve on the Adapted Kano Model Diagram they want their service to fall, as in Figure 4-1. The customer-centric group makes business decisions, including product purchasing decisions, which create an end-user experience that sits on the upper curve. The cost-reduction group minimizes business costs to the point where the end-user experience sits on the minimal satisfaction or “must-be" curve.

Subjects in the cost-reducing group were identified by their responses to why they preferred their purchased brand over the other brands. The entrepreneurs in this group made purchasing decisions focused on attributes which reduce the lifetime cost of the purchased product. Their responses all focused on the actual cost to the business for their product. This focus was typified by one respondent, "I'm only making this amount of money, the only way to make more profit is to cut costs." Another subject responded, "I prefer to buy it once and then not pay a long term recurring bill." "Higher quality means lasts longer, and won’t give you complications when using it."

Subjects using the customer-centric strategy made purchasing decisions focused on attributes which "delighted" their customers and might increase their number of customers or revenue. These respondents discussed the products in relation to how their customers perceived them. Two subjects commented that they bought air
freshener in order to attract female customers. "Ladies like the smell." "I buy air freshener to cater to the ladies." Another commented on toilet paper, "customers appreciate the softness of the tissue, they complain if I change it." When organizing the responses, an entrepreneur was grouped into the "customer-centric" group if he or she used the word "customer" in their answer. One subject summarized this strategy in their response, "Get quality products to increase customers."

4.3.3 Product Attributes

Figures 4-2, 4-3, 4-4, and 4-5, report results from the questions on which attributes the subjects considered when making a purchasing decision and which attribute was considered the most important. Figures 4-2, 4-3, 4-4, and 4-5 report results regarding
soap, toilet paper, mop and solar lanterns respectively. The attributes are split into ones which are grouped as "cost-reducing" and "customer-centric." The vertical axis is the number of respondents which either listed the attribute as one they considered or listed the attribute as the one they felt was most important to their purchasing decision. Since listing the attributes considered was an open-ended question and the subjects listed a varying number of product attributes, the total number of responses is not consistent across products. It should be noted that in these figures "cost" is cost over time to the business, not price point.

Figure 4-2: Toilet Paper Attributes

The toilet paper attributes cost, long-lasting and size are all related to the lifetime cost of the product. Long-lasting and size both refer to the length of time or number of customers for which the entrepreneur can use the toilet paper. Ease of separation, softness and thickness are all attributes of the toilet paper which improve the customer’s experience using the toilet. One nuance in understanding the entrepreneur’s decision regarding thickness, is that some subjects reported buying a slightly thicker toilet paper because customers were satisfied with fewer squares of toilet paper if the paper was thicker. One respondent bought a 2-ply toilet paper which was more expensive than the single-ply because she could use 4 squares instead of 7 squares.
and the cost per customer actually went down.

The soap attributes include individual amount control, cost, ease of stealing, size, splittable, long-lasting and form were all different forms of cost-reduction. The individual amount control was reported by respondents using liquid soap. These en-
entrepreneurs used liquid soap instead of bar soap because it allowed them to control precisely how much each customer received and therefore controlled costs. These subjects also preferred liquid soap because they felt it lasted longer for the same price because bar soap left a residue, wasted soap, on the soap dish. Ease of stealing and the ability to split into small pieces are attributes which demonstrate an interesting case of cost-reduction. Several respondents reported buying the "lower quality" brand of soap, one that performed worse on metrics like smell and ability to clean, even when the "higher quality" soap was available at the same price point. These respondents felt that the "higher quality" soap was more likely to be stolen and therefore cost more over time. It would have a shorter usable life span. This was also why they preferred soaps they had the ability to split into small pieces because if the small piece was stolen it did not represent as big a loss. Feel, performance and scent were attributes grouped as customer-centric because their use improved the customer experience. Scent in particular was the attribute that was reported to have the most affect on customer experience and therefore purchasing decisions in this group. One
franchisee bought Whitewash due to its scent which was two to three times the price of every other brand.

The solar lantern attributes of durability, cost, likelihood of theft and the solar-powered nature of the lantern were organized as cost-reducing. Durability was brought up the most often. A notable result is that many respondents thought the Sun King Pro was made out of glass and therefore less durable, going so far as to suggest metal mesh covers for the product. The Sun King Pro is actually made out of heavy plastic and is robust to large falls, but the weight and shape of the light led respondents to suggest that it was glass. Brightness, lighting time and phone charging were all ways of increasing revenue. One respondent had purchased the Sun King Pro and was using it to charge phones for money.

The mop question had fewer responses than the other products. This may reflect a lesser role in the operation of the business. The main concern when buying a mop was how long the mop lasted before needing to be replaced. A frequent problem was mop handle failure. Most respondents reported they bought the mop which they felt would last long and had a "strong" handle. This was classified as a "cost-reduction" strategy. Several respondents discussed the mop's ability to clean. This was considered to be a customer-centric attribute. One respondent listing the performance of the fabric reported that the fabric left the toilet cleaner and therefore was a better choice for their customers.

The customer-centric group was organized mainly around responses that reflected the needs of the franchisee's customer. Thirteen of the thirty-three interviews used the word "customer." Responses varied, but were put into this group if they gave a reason in terms of the customer. For example, one subject reported, "Customers prefer Ushindi because of the scent." A notable result is that these subjects were much more likely to buy products not required by their franchise contract. For example, ten of the thirteen "customer-centric" franchisees bought air freshener. The air freshener was relatively expensive compared to the other products and was not required. One of the twenty remaining entrepreneurs purchased air freshener. Another example is electric heating for the hand-washing water. The franchisees are required to provide
a tank with water and a spigot for washing hands outside of the toilet. Two of the franchisees in the "customer-centric" group bought electric heaters for the water so that the customers could wash their hands with warm water.

4.4 Discussion

The major insight from these results is the separation of the franchisees into two groups: cost-reducing and customer-centric. This can be viewed as an application of the Kano Diagram. The cost-reducing entrepreneurs are producing a product which satisfies the "must-haves" curve of the model and minimizes cost. These entrepreneurs are making purchasing decisions such as buying the soap which performs worse but will be stolen less often. The other group of entrepreneurs is buying products which "delight" the customer, such as air freshener and electric water heaters. These entrepreneurs are trying to attract more customers or repeat business through a better customer experience. One respondent specifically mentioned dominating the competition as an important driver of their strategy. While it is unclear whether there is a better strategy, it is clear that the "cost-reducing" group is larger than the customer-centric group. This fits with the economic research on the reluctant entrepreneur. The cost-reducing entrepreneurs may simply be entrepreneurs with a lower tolerance for risk. Area effects may also be producing these differences as some neighborhoods are in more commercial areas and others are more residential. The differences in average income in these areas and the differences in the level of competition may be pushing entrepreneurs towards one strategy. For example, if an entrepreneur is operating in a commercial area and needs to persuade possible customers passing by to stop in, they may be more likely to choose a "customer-centric" strategy. In contrast, if an entrepreneur is in a residential area, they may have a fixed customer base and be only able to increase profits through cost reduction. However, in the sample of entrepreneurs interviewed, the "customer-centric" group included entrepreneurs from every area.

In the previous section, revenue generation, reliability and multi-functionality were
seen as the most important attributes in product purchasing decisions. These results suggest that while revenue generation and reliability are still important characteristics, they may be separate characteristics. The designer should determine what type of strategy or customer experience the entrepreneur is looking for and design their product accordingly. In this case, the manufacturer of the public toilets has to satisfy two different groups and may choose to go after both or only consider one. The customer-centric group may be better over the long term for the franchise brand but given that the cost-reduction group is larger the manufacturer may choose to satisfy their concerns as this would allow them to achieve a greater scale.

This split also explains the observed behavior regarding the sale of toilet paper and soap. The manufacturer reported sales of 17% and 36% for their toilet paper and soap respectively. This toilet paper and soap was considered to be a high value as they were "quality" brands being offered at wholesale prices. The franchisees were choosing to buy outside options of lower "quality" at the same price point. In interviews with the field officers, estimates of 20-30% of the entrepreneurs were in the customer-centric group. This matches with the number found in the interviews and in the number buying this high-value soap and toilet paper. In fact, some of the customer-centric group may be buying soap or toilet paper which is of even higher performance.

These results are limited due to several factors. First, the interviews were carried out among franchisees of a single company in one country in one sector. This specificity allows for in-depth analysis of product purchasing decisions but does not allow for generalizations. However, these results suggest starting points for other practitioners and researchers to follow. Secondly, English was not the first language of many of the respondents. To mitigate this effect, translators were present at all interviews to clarify any questions or responses the interviewees had. In a related limitation, the nationality of the interviewer may have produced distortions in the reported answers. Subjects may have given answers that they thought the interviewer wanted. However, the interview questions did focus on factual information as much as possible. For example, asking which brand of soap the entrepreneur bought. Since the interviews were carried out on-site, the interviewer was able to confirm the
entrepreneur's answers by physically observing the products used.

4.5 Conclusions

This section reported results from thirty-three interviews with entrepreneurs running public toilet franchises in East Africa. The product attributes considered and their relative importance to product purchasing decisions for their businesses was also reported. The results were discussed and used to further refine guidelines proposed in the first section. The final guidelines for Design for Micro-Enterprise are as follows:

1. Identify micro-entrepreneurs as customers
2. Satisfy user-needs for both entrepreneur and end-user
3. Identify business strategy or desired customer experience of micro-entrepreneur
4. Align product attributes with this strategy

In this case the micro-entrepreneurs were split into two strategies: cost-reduction and customer-centric. The customer-centric group bought air freshener and were concerned with the softness of the toilet paper, brightness of the solar lantern and the temperature of the hand-washing water. The cost-reduction group made decisions based on lifetime cost and were concerned with the durability of the solar lantern, the minimum amount of toilet paper for customer satisfaction, the durability of the mop, the likelihood of theft of the soap and the ability to control the amount of soap given to an individual customer. Which group the manufacturer targets depends on the manufacturer's strategy, but the larger lesson is that the designer and manufacturer can balance the needs of the end-user and of the micro-entrepreneur by evaluating the entrepreneur's strategy for customer experience.

In conclusion, this section answered the following questions:

1. What factors affect a micro-entrepreneur's decision to buy a product?

Many factors affected the micro-entrepreneurs' purchasing decisions, including where they learned about the product, the cost over time, and the entrepreneur's
vision for user experience. One notable result is that the level of business knowledge of the entrepreneur did not seem to affect the micro-entrepreneurs’ decision process. The interview subjects easily produced many of the important financial calculations regarding cost, inventory and profits and how these calculations affected their decisions. Finally, individual risk preferences and how that effected the business strategy was crucial to the purchase decision process.

2. Which product attributes contribute to the purchasing decision?

A wide range of attributes were considered by the entrepreneurs and can be split into two groups: cost-reducing attributes such as durability, serviceability, maintainability, and likelihood of theft; and customer-centric attributes such as performance, ability to delight and multi-functionality.

3. Which product attributes are the most important to the purchasing decision?

The most important product attributes changed depending on the business strategy selected. The most important attributes for the cost-reduction strategy minimized the lifetime cost of the product. The most important attributes for the customer-centric strategy increased revenue by attracting more customers.
Chapter 5

Contributions and Conclusions

This thesis addresses system-level approaches to complex design tasks. The thesis outlines related work from formal methods for design to studies of human design team behavior. In the second chapter, interviews with designers at a large aerospace organization are presented and simulations of the results are demonstrated. The third chapter proposes a new approach to product design for emerging markets, Design for Micro-Enterprise. This framework is refined in the fourth chapter using interviews of micro-entrepreneurs from East Africa. One major theme in this work is the use of system-level approaches in real-world design situations.

5.1 Biased Information Passing

Chapter Two presented work on negotiation strategies between sub-systems of design teams performing large-scale complex system design tasks. This thesis contributes a new model for understanding how design teams perform this task through the concept of biased information passing. This work simulates the effect of three possible strategies for biased information passing. In doing so, this thesis quantitatively estimates the effect of this behavior on optimality and speed. The major finding from this work is that biased information passing as defined in this work is an issue real-world design teams are currently facing in complex system design and that the strategies reported by interviewees have a negative effect on optimality and speed across a wide range of
5.2 Design for Micro-Enterprise

Chapter Three presented work on approaches to product design for emerging markets. This thesis contributed a new set of guidelines for performing these design tasks. The framework, Design for Micro-Enterprise, advocates for a higher systems-level view that simultaneously takes both the needs of the end-user and the micro-entrepreneur into account. The guidelines are based on interviews with practitioners and case studies. The guidelines stated that revenue generation, product reliability and serviceability, and multi-functionality were key to product success. This work suggests new directions for designers and researchers in terms of a focus on micro-enterprise products for emerging markets and an approach for designing them.

5.3 Field Experiment

Chapter Four presented results from a field study on purchasing decisions of micro-entrepreneurs in East Africa. Notable contributions include the refinement of the Design for Micro-Enterprise framework and the use of the Kano model to categorize business strategies. The field study validated the framework by finding that revenue generation and product reliability were key factors in determining the product purchasing decision of the entrepreneur and therefore the success of the product. The framework was improved by demonstrating that in this case, these factors were requirements of separate groups of entrepreneurs. The important finding is that the designer should focus on the business strategy or vision of the micro-entrepreneur and this will help the designer manage the competing stakeholder objectives. Secondly, this work makes a novel use of the Kano model to describe the business strategies of micro-entrepreneurs. This new model can support designers as they define functional requirements from user needs for entrepreneurs in this market.
5.4 Conclusions

The above contributions are the notable findings from the work presented in this thesis. This work concludes that the use of system-level thinking can be a successful approach for balancing competing stakeholder objectives.

1. How do practitioners currently balance competing objectives in complex systems with many stakeholders?

   Practitioners currently balance competing objectives using a variety of strategies but are focusing on sub-system level objectives. In the aerospace context, sub-systems prioritized sub-system level outcomes and communicated with each other in sub-optimal ways. In the emerging markets context, many practitioners focus on a end-user centered approach with a focus on early-stage design.

2. How do these practices change given the context of the complex system?

   The two studied contexts differed in their approach mainly because of the level of involvement in the design process of the stakeholders. In the aerospace context, the stakeholders were negotiating throughout the design process, while in the emerging market case, stakeholders were simply purchasing or not purchasing the products. There were several common themes, including a lack of system-level thinking and a focus on single objectives. For example, in the emerging market case, practitioners have been focusing solely on the end-user, but this research shows that some practitioners have been finding success by expanding the focus a larger system-level view and including micro-entrepreneurs.

3. How does the human decision process for balancing competing objectives differ from formal strategies?

   As seen in both the aerospace and emerging markets cases, the decision process for the design teams differed greatly from formal methods. In both cases, a lack of system-level perspective made balancing competing objectives difficult and led to sub-optimal solutions.
4. What is a successful approach to balancing stakeholder interests throughout the design process?

In the emerging market context, one successful approach according to the designers interviewed and the case study analysis was the expansion of focus to more stakeholders. By focusing on both end-users and micro-entrepreneurs some enterprises have been finding more product success. This may be due to a better alignment of objectives between the manufacturer, customer and other stakeholders.

5.5 Future Work

This thesis makes contributions to the areas of complex system design and design for emerging markets. Future work in complex system design should involve investigating more organizations to see if the use of biased information passing as defined in this study is widespread. Secondly, the simulations investigating the size of the effect were simplified to two-player systems. Future work should involve simulations of larger systems as well as real-world problems.

Similarly, future work in design for emerging markets should investigate more organizations and products in-depth to see if these factors are key to product success outside of East Africa. Also, validation of the method through implementation in a design team would allow for further refinement of the guidelines. It is the author's hope that Design for Micro-Enterprise is the beginning of a conversation about designing enterprise products for small businesses in emerging markets in the design research field. Expansion of the focus to other stakeholders in the system may also yield notable results.
Bibliography


