Exploring ‘Designer Context’ in Engineering Design:
The Relationship Between Self, Environment, and Design Methods

by

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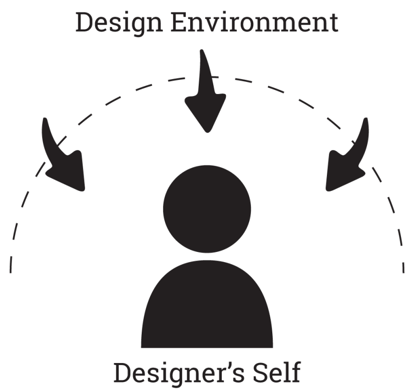
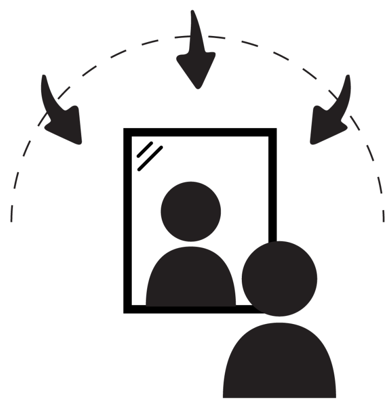


1. Define and acknowledge designer context



2. Reflect on designer context

3. Create more equitable and positive outcomes

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ABSTRACT

Engineering design methods support engineers' decision-making throughout a design process in order to improve design outcomes. The selection and implementation of suitable design methods are therefore critical to project success. Prior engineering design research has focused on designers' professional experiences or the problem context for guiding method choices. Perhaps due to disciplinary norms of objectivity, individual characteristics outside of an engineer's professional expertise are not seen as influential on design outcomes. In contrast, theories from other design disciplines define aspects of a designer's experience outside of their professional self as central to design practice.

This dissertation seeks to reconcile these two paradigms by exploring whether 'designer context' factors, that are often not discussed in engineering design but are found in other design fields (i.e. - organizational culture, gender, race) can impact design outcomes via method selection and implementation. Results from practitioner interviews on designer context and prototyping methods, as well as an empirical study of a novel design method, suggest that a broad range of designer context factors can influence design method selection and implementation, ultimately impacting the efficiency and efficacy of a design process. Therefore, if engineering designers were to consider their holistic designer context and its influence on their work, as occurs in other design fields, better engineering outcomes could be achieved.

An exploratory study consisting of qualitative interviews formalized designer context and illustrated how these contextual factors impacted methods used by practitioners in the medical device industry. This study provides an initial foundation of designer context factors for exploration in future research and practice. These factors were categorized into the Design Environment, or the external factors surrounding a designer when they are designing, and the Designer's Self, or the internal factors related to a designer.

Interviews with design practitioners from small-to-medium sized enterprises in Rwanda and Kenya revealed specific resource constraints impacting the implementation of prototyping methods. Many of the identified constraints were related to the practitioners' context. Limited access to quality materials or fabricators, often due to difficulties navigating a decentralized market, added time and cost to the process. Practitioners reported trying to develop simple, functional, and physical prototypes with increasing fidelity through a highly iterative process. However, these con-

straints negatively impacted the chosen prototyping method, suggesting that alternative methods could be beneficial.

In an empirical study, our team proposed and implemented a new method for considering multiple stakeholder preferences, the Stakeholder Agreement Metric (SAM) framework, to support the design of a hand tool to reduce injuries for informal electronic-waste (e-waste) recyclers in rural Thailand. This method was compared to the Analytical Hierarchy Process (AHP), an existing method that supports similar decisions. Results showed that the SAM framework outperformed AHP in this informal setting due to the failed completion of AHP by participants. The study highlights how designer context not only influenced the implementation of design methods but also their development.

This dissertation expands the boundaries of what factors should be considered influential on design processes and their outcomes. Across all three studies, designer context was shown to influence method selection and implementation. The findings suggest that contextual factors affect design methods in practice and should be included in future research to enable the selection and implementation of more suitable and effective design methods.

CHAPTER 1

Motivation and Overview

1.1 Introduction

In our increasingly data-driven world, technology continues to be designed by engineers upon whatever data is collected and used. There have been countless examples of the results of technology that amplifies existing inequities based on the lack of representation in design. For example, automotive design was historically defined by men, resulting in decades of crash testing only with dummies modeled after the average male. Consequently, female drivers are 47% more likely to sustain severe injuries than male drivers in a similar car crash [1]. Only in 2011 were the first female crash dummies required in safety testing, trying to make up for the 60 years of cars on the road that were largely unsafe for women [2]. There are also countless cases of racism in automation technologies and algorithms involved in the growing number of technologies utilizing artificial intelligence and machine learning. For autonomous vehicles, one study showed that white pedestrians were 10% more likely to be correctly identified as a pedestrian than Black pedestrians [3], which translates to a currently unsafe design outcome. One common thread in these cases is the lack of representation in diversity on the engineering teams designing these systems, which can result in designs that do not achieve their intended goals and that are unsafe for a large proportion of the population. My work is motivated by this common power imbalance in engineering between the designers and their intended users and the resulting negative design outcomes. To create improved design systems, my work aims to push for the basic step toward equity of reflecting on our own selves as designers in order to help us identify gaps in our design processes and target better representation in design.

Engineering design can be modeled as a decision-making process, where engineers make a collection of design decisions to achieve a certain design outcome [4–7]. Researchers have suggested many different design methods to improve their decision-making process. This dissertation uses Nigel Cross's definition of design methods as "any procedures, techniques, aids or 'tools' for designing" [8]. Given the large number of design methods available, engineers intentionally or unintentionally choose what design methods to use throughout their process [5, 8–10].

Many inputs can contribute to the selection and implementation of suitable design methods, such as the user, the location, and the design task at hand. For example, for designers who want outcomes to be valuable to a wider range of potential users, inclusive design methods exist to support their design decisions [11, 12]. Other researchers describe recommended methods and practices for prototyping, requirements development, and other design tasks [8, 10, 13, 14]. The goals of these methods are often to improve prototyping processes or the requirements gathered that are designed upon in order to create products that reduce the mismatch between designer intent and the user's actual experience [13, 15]. Therefore, selecting and implementing suitable methods by considering these different factors and the design stage or task is important for realizing targeted design outcomes [8].

The majority of these factors described in engineering design literature are related to technical considerations or the user's context. Engineering as a field has historically emphasized technical rationality and objectivity in its approaches, resulting in limited discussion of the engineering designer's own self in relation to their design processes. However, in the 1980s, Schön introduced the paradigm of the reflective practitioner, which some researchers have since started to investigate deeper in engineering design [16–18]. While these studies have shown that reflective practices in engineering design are also indicative of effective design practice, there is still limited work that delves into what designer experiences can actually entail when utilizing them for design practice. Existing work includes investigation of various methods used by novice and experienced designers [13, 14, 16, 19, 20] and the consideration of the designer's manufacturing and assembly requirements when choosing design methods [10]. My work aims to add to this body of work by expanding the boundaries of what factors have been considered influential on engineering design processes, especially those related to the designer.

My dissertation formalizes the consideration of 'designer context' factors and explores their relationship to different design methods. Designer context is defined here as (1) the Designer's Self, or the internal factors related to a designer, such as social identities and (2) the Design Environment, or the external factors surrounding a designer when they are designing, such as organizational size and culture. Designer context factors are proposed as an additional set of considerations that can influence the selection and implementation of suitable design methods and therefore, the effectiveness of those methods in terms of its design outcomes.

1.2 Contribution and Chapter Overviews

This dissertation builds upon the bodies of work in engineering design that develop, apply, and test different design methods to improve design outcomes. This literature includes a large amount of research on user context and the corresponding proposed methods for engineering designers to consider that context throughout their design process. My work identifies and addresses the gap of exploring how designer context may also influence design methods that are used in a design process and therefore later design outcomes.

My dissertation begins with a background on engineering design literature on methods and context as well as a brief overview of designer context factors considered in other design fields outside of engineering (Chapter 2). My first study formalized and defined 'designer context' and explored what and how designer context factors emerge for engineering design practitioners in the medical device industry through a qualitative exploratory study (Chapter 3). My second study investigated prototyping methods used by practitioners in small-to-medium sized enterprises in East Africa through a qualitative study. This study found how certain designer context factors, especially those related to resource access, influenced the prototyping methods the practitioners used (Chapter 4). My last study proposed a method to assist with managing multiple stakeholder preferences and compared it to an existing method using an empirical case study based on an actual field intervention and study I helped conduct in Thailand. Through this empirical study, I learned how our own context as the designers of the intervention impacted the methods we used during the project (Chapter 5). Together, these studies define and explore designer context factors and show that they can influence the design methods that engineering designers use, which can, in turn, impact the design process and its outcomes. I then discuss how these findings add to the current state of work, the limitations of my work, and the implications for future research, practice, and engineering education (Chapter 6).

CHAPTER 2

Background

2.1 Engineering Design Methods

During the engineering design process, a designer must make many decisions to achieve targeted design outcomes. Because of the wide variety of design activities involved in these decisions, a rich body of engineering design research centers on design methods to support these design decision-making processes. This dissertation uses Nigel Cross's broad definition of design methods as "any procedures, techniques, aids or 'tools' for designing". Cross describes design methods as the series of activities that designers use, which comprise an overall design process. Researchers are constantly refining methods for practitioners to use for different situations to achieve better product results [8].

Many recommended engineering design methods exist to support essential activities during a design process. One such activity is prototyping, for which researchers have examined strategies such as creating physical or nonphysical 'quick and dirty' prototypes, using multiple and varied prototypes throughout a design process, or following Menold et al.'s Prototype for X framework and making prototyping decisions based on a chosen prototyping frame (e.g. - desirability, feasibility, viability) [13, 21]. Another example of an essential design activity is information gathering, which also occurs throughout a design process but especially during preference elicitation and requirements development activities. Methods for information gathering include interviewing stakeholders, conducting a literature search, competitive benchmarking, consulting experts, focus groups, and surveys [10, 22]. Different methods also exist to help with prioritizing requirements gathered from various stakeholders such as quantitative multi-criteria decision making methods [23]. This dissertation draws upon the engineering design methods literature in order to define and categorize methods used by engineering designers when analyzing the potential influences of designer context factors on methods.

2.2 Incorporation of Context into Engineering Design Method Selection

2.2.1 User Context

There is a growing recognition that practitioners need support tools for considering user context in design method selection to create designs that can meet user needs. For example, the Prototype for X framework aims to build upon existing prototyping strategies by incorporating more user-centered considerations such as usability or user satisfaction when choosing what prototyping methods to use [21]. Another aspect of considering user context is empathic design, which includes different techniques for building empathy depending on how close to the user context that the designer can or will get, ranging from role-play and simulation to direct contact with users [11]. Additionally, there is emerging work around considering user context for achieving universal or inclusive design, including methods targeted toward appreciating user capabilities such as the use of action-function diagrams [12, 24, 25].

Some researchers have also considered user context, specific to Engineering for Global Development (EGD) projects for design method selection. In these types of projects, the user's context is often unfamiliar to the designer [26]. Many researchers have examined or created design methods for engineers to use in these cases. For example, Wood and Mattson introduce the Design for the Developing World Canvas in response to the common engineering design pitfalls they found, such as not properly understanding the user's language, culture, and context [27]. Aranda-Jan et al. present their holistic framework of contextual factors, such as religious and cultural beliefs and economic capacity, that can be used by designers to gain a better understanding of the context of use when creating medical devices for low-resource settings [28]. Some researchers have also taken a broader look at the existing research on the incorporation of user context on design method selection in these settings. Jagtap found that researchers have looked into different attributes of user context such as income, rural and urban, and countries, while Burleson et al. recently conducted a review that also details the variations of contextual considerations suggested for engineering design processes, including design method selection [29, 30]. As much of the contextual incorporation in engineering design revolves around user context, this paper draws upon this literature to inform potential analogous designer context factors that could be explored in this study and in future work.

2.2.2 Designer Context

The ideas of objectivity, neutrality, meritocracy, and depoliticization is deeply embedded in engineering education, research, and practice [31]. Physics and math lie at the basis of core engineering techniques and analysis. These technical aspects of engineering are often perceived to be objective and neutral, where physics does not change based on who the engineer is. Because of these engineering norms founded in objective engineering analysis, the idea of meritocracy, where society rewards the most talented and hard-working people, is lauded: engineering outcomes depends on how good one is at being an engineer and what the problem is. “Political” aspects such as power, discrimination, and inequities are unrelated [31].

These constructs are reflected in the focuses of engineering design research. One large area of research is on the designer’s level of experience or expertise and how that might influence design method selections. For example, several researchers have applied Schön’s work on the reflective practitioner to engineering designers in order to better understand the design practices and behaviors that exist [16–18]. In these cases, the discussion of reflective practice revolves around the engineering designer’s knowledge and understanding of the design problem and where that knowledge comes from, which is often from practice. In a similar vein, a large body of work in engineering design also examines and compares the design practices used by novice designers compared to experienced designers [19, 20]. Deininger et al. found that novice designers infrequently used cheap prototypes early on in a design process or to help define user requirements, though these are recommended prototyping practices [13]. Research has also shown that expert or experienced designers tend to spend more time gathering a variety of information to inform design tasks which can impact the validity of design requirements developed [14, 20]. Recent literature in engineering design has also explored specific facets of a designer’s self, professional identities, and how they relate to professional roles and behavior [32, 33]. These bodies of work focus on reflecting primarily on the designer’s professional experiences and expertise.

Another common area of investigation in engineering design related to the designer context is of the technical constraints that designers may face. Ulrich et al. explain early on in their “Product Design and Development” textbook that manufacturing capabilities, capacities, and constraints of their operations must be considered during design. These considerations include what suppliers or internal facilities can and should be used [22]. Their textbook and Dieter and Schmidt’s textbook, “Engineering Design”, include an entire chapter on design for manufacturing methods, which include designing components to eliminate process steps during fabrication or including a draft, or taper, on vertical surfaces of designs so castings can be more easily removed from molds [10, 22]. Notably, many of these technical constraints are described in these engineering design sources with an assumed manufacturing context in mind - one which allows access to specific manufacturing processes that many contexts may not have.

In some EGD literature, researchers peripherally discuss certain designer context factors, often due to the frequent differences from the user context [26]. For example, Nieusma and Riley point out the power imbalances related to the differences in language and socioeconomic status of the designer compared to the user [34]. Similarly, many of the pitfalls that Wood and Mattson describe are related to the differences in language and culture between the designer and their targeted users [27], and they advance that investigation toward the factors' effects on design ethnography [35]. My work aims to add to this body of work by expanding the boundaries of what designer context factors have been considered influential on engineering design processes and centralizing my contextual exploration around those designer context factors.

2.3 Consideration of the Designer's Self Across Design Fields

Outside of just engineering design, many design fields, such as art and design, human-computer interaction, and urban planning, have followed a reflexive turn, similar to that which occurred in the 1980s in fields such as anthropology and sociology [36]. Unlike engineering design, these design fields have centralized discussions about a designer's social identities such as gender, sexual orientation, race, ability status, and the intersectionality of identities [37, 38, 38–48]. These researchers described the importance of considering these designer identities and their impacts on subsequent designs that are propagated throughout technology and cities, acknowledging the inherently political and subjective nature of design. Dombrowski et al. explicitly called out that taking a social justice-oriented approach for interaction design "involves active reflection on how designers' own beliefs and values influence design processes and outcomes" [49].

Many phrases have come to describe design that aims to create positive social impact and achieve sustainability, including the reflection on a designer's role in doing so. Some phrases include responsible design and design activism. Jesse Tatum stated that designers must acknowledge themselves and their goals as well as the realities of politics, judgment, and undetermination in order to contribute meaningfully to responsible design. He described: "The science we have, and the technology we have both are always and inevitably a function not simply of "reality," but of where our attention happens to be focused" [50]. Researchers also described socially responsible design as it relates to corporate social responsibility and the triple bottom line [51–53]. Building off the discussion in Victor Papanek's Design for the Real World, researchers acknowledged the need for understanding the designer's role in achieving socially responsible design outcomes in business and corporate settings [52, 53]. Design activism similarly represents the idea of design's role in promoting positive social impacts, requiring a similar examination of the role of designers or design activists [54, 55]. For example, Fox et al. assessed the roles of designer positionality and politics on design interventions, especially as used for design activism [56].

Many organizations have adopted and formulated their own versions of designing for positive social impact in practice, each acknowledging the importance of reflecting on the designer's own self and the political nature of design. Much of these practice-based frameworks target equity, social justice, and redesigning existing systems as design goals, where reflection of the designer's self is required to acknowledge and dismantle existing power imbalances. The Center for Socially Engaged Design (C-SED) at the University of Michigan is one such organization and provides its own design process model and educational workshops and curriculum, which embed designer reflection, in order to achieve what they call socially-engaged design [57]. The Creative Reaction Lab is another organization that developed their "Equity-Centered Community Design Field Guide" in order to guide people through a design process model that can lead toward inclusive and equitable outcomes [58]. One design researcher developed "A Social Designer's Field Guide to Power Literacy" in order to walk designers through participatory processes that can fight systems of oppression [59]. This field guide helps build reflexivity in designers by including reflective activities such as a social identity wheel and questions on who was included and excluded from a design process. My dissertation draws from this wide body of research and practice in order to examine the role of the designer's self in engineering design and how they manifest for practitioners during design processes.

2.4 Research Gap

Engineering design research often follows the deep roots of objectivity, neutrality, meritocracy, and depoliticization which frames much of the engineering field. However, this approach fails to properly acknowledge and consider that design fundamentally involves people and values. The decisions made by engineering designers during method selection and implementation are often attributed to what the problem is (i.e. - knowing your end-users), their professional skills gained as an engineer, or their technical constraints. To constitute "engineering design," the people-based ideals of design must be reconciled with the objective ideals of engineering. Other design fields, such as art and design, human-computer interaction, urban planning, and many social justice-oriented design organizations in practice, have acknowledged that designers and their values impact their design outcomes. We must learn how to apply designer-focused assessment, found in these other design fields, to problems faced in engineering design, such as those that have technical performance of a product embedded in the process.

My dissertation aims to complement the existing engineering design literature by explicitly examining the consideration of designer context factors in engineering design method selection and implementation. In the following text, my use of "designer" refers specifically to engineering designers based on the realm of work in which my research is situated. I discuss designer context as two components: (1) the Designer's Self, or the internal factors related to a designer, such as social identities and (2) the Design Environment, or the external factors surrounding a designer when they are designing, such as organizational size and culture. My work draws two parallels with existing literature and design practice. Designer context provides a parallel consideration to user context, which is commonly examined in engineering design. This work also draws from the designer context work done in other design fields and in practice and investigates aspects that should be actively considered in engineering design research. My dissertation provides an exploratory and holistic view of designer context factors and their potential relationship to the design methods that engineering designers use in response to my overall research question: how might designer context influence design method selection and implementation in engineering design?

CHAPTER 3

Formalizing 'Designer Context' and Its Relationship to Engineering Design Methods

This chapter was coauthored with Jesse Austin-Breneman.

3.1 Abstract

Engineering design researchers develop and refine design methods to help tailor design activities to the situation at hand in order to enable engineers to achieve improved design outcomes. Considerations for design method selection and implementation center around the problem or user context, the engineer's professional experience, and technical constraints. However, these considerations are rooted in the objectivity and meritocracy that characterize the overall field of engineering and do not consider the people-centric aspect of design, which other design fields acknowledge. The engineering design literature lacks the formalized consideration of the broader aspects related to the designer's own context in design method selection and implementation. This research reconciles the objective approaches of engineering and the people-based approaches conducted in other design fields, such as human-computer interaction, in order to understand what aspects of designers we should examine more closely for engineering design. This study formalizes and defines 'designer context', understand what additional designer context factors engineering design practitioners have considered during design, and how these factors might relate to the design methods they use. Semi-structured interviews were conducted with 11 practitioners in the medical device industry and results were found using qualitative coding and thematic analysis. Many designer context factors were found and categorized into Design Environment factors, or the external factors surrounding a designer when they are designing, such as organizational size and team composition, and Designer's Self factors, or internal factors related to a designer, such as their confidence or gender identity. Overall, practitioners reported many different cases where different aspects of their designer context influenced their design method selection and implementation, often by

changing what method they could use or affecting the quality of their method implementation due to constraints or enablers in their own context.

3.2 Introduction

Many design methods exist to support essential design activities during engineering design to improve targeted design outcomes. Many factors, such as user context, are incorporated into design method selection and implementation to help engineers tailor their actions to different situations. Additional contextual factors include specific facets of a designer's own context such as their experience level or their manufacturing constraints. However, other designer context factors such as social identities or organizational culture are not explored or only peripherally discussed in the literature as they relate to design methods. Therefore, engineering design literature lacks a formalized exploration of designer context factors and their potential impacts on design method selection and implementation.

Through a qualitative study, this paper explores and defines what designer context factors are actively considered in practice by engineering designers and how those factors might relate to the design methods used. This paper aims to contribute to the broader discussion of improving design outcomes by formalizing the consideration of designer context factors for design method selection and implementation. The research questions are as follows:

1. What factors of designer context do engineering design practitioners consider in practice?

2. How do designer context factors relate to the design methods used by engineering design practitioners?

3.3 Methodology

A qualitative approach was used to collect in-depth, rich descriptions that would complement the exploratory nature of this study.

3.3.1 Participants

The medical device industry was chosen as the target industry for this study due to the overarching design and development process constraints mainly related to strict regulatory requirements from the Food and Drug Administration (FDA) and other regulatory bodies [60]. This restricted design process lends itself to study and to better understand designer context factors within the constraints of this one particular industry. Participants were recruited through existing contacts or cold emailing medical device companies identified based on size and location to see if any employees would be willing to participate. Criteria for selection included working or having recently worked at a medical device company with main job functions that were related to engineering design, including job titles such as Research and Design Engineer or Product Design Engineer. The study participants included 11 design practitioners (Table 3.1).

Table 3.1: PARTICIPANTS.

ID	Location	Gender Identity	Age	Race and Ethnicity	Degree	Design Experience (years)	Company Size
P1	USA	Female	23	Asian	BS	2.5	Small
P2	USA	Male	32	White	BS	11	Small
P3	Switzerland	Female	32	White	PhD	7	Large
P4	USA	Female	24	American Indian or Alaskan Native, Black or African-American, Hispanic, White	BS	1	Small
P5	USA	Male	27	White	BS	3	Small
P6	USA	Male	32	White	BS	10	Large
P7	France	Male	26	Moroccan	MS	3	Small
P8	USA	Male	26	White	MS	5	Large
P9	USA	Female	35	White	PhD	10	Large
P10	USA	Male	29	White	BS	3	Small
P11	UK	Male	27	Asian	MS	4	Small

3.3.2 Data Collection

Semi-structured interview data was collected for this study. Before the interview, participants were asked to complete a brief survey to enable the collection of the professional and demographic background information that is shown in Table 3.1. Participants filled out the survey at least a day before their interviews in order to reduce the potential priming of the interview. Each participant engaged in one interview with a developed protocol over phone or video call that lasted between 75-90 minutes. The interviews were structured in three sections as shown in Table 3.2.

In Section 3 of the interview, participants were shown 3 different lists of factors (Table 3.3) that were chosen based on design literature and social identities examples. The factors were broken down into separate lists and some factors were grouped in the same bullet point in order to reduce participant fatigue. Participants were asked to take as much time as they needed to think through each factor. The purpose of this section was to capture any factors that may not have been discussed

Table 3.2: INTERVIEW STRUCTURE AND QUESTIONS.

Section	Example Questions
1: Industry Project	• Tell me about a recent design project you've recently worked on. • Can you walk me through the steps of how you came to decision X? • How do you think your personal background influenced any of your decisions? • How did the design environment around you influence any of your decisions?
2: Design Scenario	You are on a team tasked with designing a drinking water fountain for a picnic area in a public park. • What information would you aim to gather? • How would you go about gathering this information? • How do you think your background influenced what information you thought was important? • How do you think your background influenced how you'd gather that information? • How would different elements of your design environment change your process of gathering this information?
3: Designer Context Factors	• How have you considered this factor in your design projects, if at all? • Please provide a brief example for each.

throughout the first two sections. Participants were asked to consider the factors in reference to their own selves, not their end-users.

3.3.3 Data Analysis

Audio recordings of the 11 interviews were transcribed, checked against the recordings for accuracy, and de-identified using pseudonyms. The analysis was inductive and emergent, in which initial coding was performed on several interviews. These initial codes were refined based on iterative analysis of patterns in the data and input from the literature [61], including existing classifications of factors and methods defined in literature [10, 33, 62–68]. All of the refined codes were integrated into two codebooks for factors and methods, respectively, where definitions and example quotes were developed and assigned and the factors codes were grouped into broader categories for organization.

With the said codebooks, data were coded such that relationships with factors and methods could be established. Throughout the analysis, an emphasis was given to finding factors, and

Table 3.3: LISTS OF FACTORS SHOWN IN INTERVIEW SECTION 3.

Personal & Social Identities	• Age • Gender, Sexual Orientation • Race, Ethnicity, Nationality • (Dis)Ability Status • Socioeconomic Status • Language Proficiency
Professional Identities	• Level of Expertise, Education Level • (In)Formal Job Functions
Organizational & Environmental Factors	• Design Team Composition • Organizational Size, Culture, Structure • Access to Testing, Design Resources • Funding Source(s) • External Partnerships • Local Environmental Conditions

only methods that had a clear connection with a factor explicitly mentioned in the participants' interviews were included in the analysis. Therefore, methods that appeared by themselves were not a focus of this analysis. Instead, the coded excerpts for the factors were examined in depth to pull out those that described a connection to design methods used by participants. The methods were coded inductively, then refined based on design methods from literature, primarily engineering design textbooks [10, 22, 69, 70]. From the extracted coded excerpts, trends in the relationships between factors and methods were identified.

3.4 Results

The designer context factors that emerged from the 11 interviews after qualitative coding and thematic analysis were organized into three hierarchical levels, shown in Table 3.4. The individual designer context factors were organized into categories such as Resource Allocation or Professional Self. These categories were then organized into two types: (1) Design Environment, or the external factors surrounding a designer when they are designing and (2) Designer's Self, or the internal factors related to a designer.

The results are presented here by first listing and defining the Design Environment factors that emerged and the three categories into which they were organized (Table 3.6). In the text following

Table 3.4: HIERARCHICAL LEVELS OF DESIGNER CONTEXT.

Type	Category	Individual Factors
Design Environment	• Resource Allocation	Funding constraints, schedule constraints, ...
	• Organizational Characteristics	Organizational size, team composition, ...
	• Market Characteristics	Legal and regulatory requirements, product reach
Designer's Self	• Professional Self	Practice-based knowledge, learning style, ...
	• Internal Motivators	Motivation, personal ethics, ...
	• Social Identities	Ability status, gender identity, ...

the table, nuanced descriptions of the relationships between designer context factors and design methods used are provided (Sections 3.4.1.1, 3.4.1.2, 3.4.1.3). The same is done for the Designer's Self factors and relationships to design methods in Table 3.7 and Sections 3.4.2.1, 3.4.2.2, and 3.4.2.3, respectively.

The definition of design methods used for these results is "any procedures, techniques, aids or 'tools' for designing" [71]. The total list of methods that emerged as those influenced by designer context is shown in Table 3.5. The list includes individual methods and collections of methods, such as Design for Manufacture, and is organized by design activity. Appendix A lists each method and its definition used. While data was analyzed to find relationships between factors and design methods, additional effects were also found on a broader design process level. For example, designer context was found to influence how practitioners communicated with their teammates, external stakeholders, and across business functions, as well as the project's overall scope or existence.

3.4.1 Design Environment

The external Design Environment factors that were found were organized into the following three categories:

- **Resource Allocation**: factors related to access to and management of organizational assets
- **Organizational Characteristics**: qualities that are tied to the organization itself

Table 3.5: METHODS INFLUENCED BY DESIGNER CONTEXT.

Information Gathering	**Requirements Development**	**Concept Testing**
Company-centered information	Define customer requirements	Determine test plans
Competitive benchmarking	Classify requirements	Bench testing
Codes and standards		Prototype and test
Customer complaints	**Ideation**	Simulated use testing
Customer surveys	Brainstorming	Use of test standards
Design team's own experience	Checklist	
Document use environment	Implement (parts of) existing solutions	**Risk Analysis**
Engineering analysis	Stimulate creative thinking	Functional design validation
External expert consultation		Failure analysis
Focus groups	**Concept Selection**	Failure Mode Effects and Analysis (FMEA)
Internet search	Choosing first concept in mind	
Interviews	Decision matrices	**Additional Methods**
Literature search	External decision	Design for Manufacture (DFM)
Observation	Intuition	Design for Assembly (DFA)
Patent search	Multivoting	Consider distribution for design
	Pros and cons	Provide clear work instructions
Stakeholder Analysis	Targeted concept refinement	Documentation of approach
Identify stakeholders		Material selection
Prioritize stakeholders		Concurrent engineering
Stakeholder cost-benefit analysis		

- **Market Characteristics**: qualities related to an organization's competitive strategy in the market

Table 3.6 shows the Design Environment factors that emerged from the interviews, the definition of the factor, and an example quote demonstrating the factor. The factors are organized by the three categories described above.

Table 3.6: DESIGN ENVIRONMENT FACTORS.

Factor	**Definition**	**Example Quote** (Participant ID)
RESOURCE ALLOCATION		
Access to tangible design resources	The ability to acquire and use tangible resources (i.e.-software, materials, people, equipment)	"We would have liked to have more access to testing, to be able to test more often our products. But we didn't have the machines or the hardware to do it." (P7)
Funding constraints	Factors related to budget size and source of funding	"Anytime I go into a project...I'm very closely scrutinizing the funding source...trying to find out what's the runway,...who is the source, and what's the likelihood that they will add more funding later down the road if needed." (P2)

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Table 3.6 – Continued from previous page

Factor	**Definition**	**Example Quote** (Participant ID)
Schedule constraints	Time and schedule constraints related to the project	"There's big lead times and time is constrained, time is always constrained." (P5)
Priorities of management	The priorities of higher managers that impact the individual's projects and tasks	"With a lot of projects that are going on, I'll have a software team member that I rely heavily on, but that might get pulled off for a couple of weeks at a time to support another urgent project and stuff like that too." (P8)
ORGANIZATIONAL CHARACTERISTICS		
Organizational size	The number of employees in the organization	"It's really small. There're technically five members plus a technical advisor, but really only three of us" (P1)
Organizational structure	The formal allocation of work roles and the administrative mechanisms to control and integrate work activities including those which cross formal organizational boundaries [65]	"I work for a specific business unit of a much larger organization...you basically have those four groups...outside of that, we have our marketing function, we have sales...our medical affairs group, quality function...operations...We have regulatory...we have legal as well" (P6)
Organizational culture	The values, beliefs, and underlying assumptions that are collectively and historically held at an organization [67]	"Again, no one told us to work on this project. We were just like, "Oh, this might work." So we both decided to just, in true startup culture, just do it... So we cast it and melt-molded it, and it turns out this material works" (P4)
Team composition	The configuration of member attributes in a team [64]	"It's a lot more multidisciplinary. We have a lawyer, or a doctor, and an engineer on the team" (P11)
Workspace	The physical area the designer works in	"When there's whiteboards around, when there's places where you can draw your ideas, it definitely helps" (P10)

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Table 3.6 – Continued from previous page

Factor	Definition	**Example Quote** (Participant ID)
Supply chain constraints and enablers	Factors related to the organization's supply chain network, including suppliers, manufacturers, and distributors	"We buy them from a supplier, they're already made but unfortunately they are not really plug and play like a regular 2D printer...there was really a lot of development to get all the parameters right" (P3)
Industry norms	Factors related to the overall type of industry or sector that the organization is within	"I think a lot of my biases come from working in health and med device. It's different that I have a lot of biases and opinions because I've been engaged in health as a whole in the field for a long time. And I think that if I worked in environmental engineering or in water or oil, I think a lot of my opinions versus what I work on might be really different too." (P1)
MARKET CHARACTERISTICS		
Legal and regulatory requirements	Factors related to laws and regulations they must follow and related processes	"With the water fountain… regulations, laws, rules, limitations due to environmental conditions, anything like that is going to be considered. For other medical companies, just constantly thinking about regulatory requirements. Keeps me up at night" (P2)
Product reach	The locations of where the company's products are sold	"We are a global company and our products are not just sold in one particular area." (P6)

3.4.1.1 Resource Allocation and Design Methods

Two Resource Allocation factors, access to tangible design resources and funding constraints, notably affected the design methods used. There were several cases where access to tangible design resources changed the participants' methods, especially around testing and validation. For example, P8 described how having access to in-house prototyping equipment allowed for the implementation of prototyping and testing to validate ideas and communicate with others:

> We have a nice little prototyping setup. We have a couple 3D printers and any kind of hand tool you could imagine, and then downstairs is a machine shop. One big impact it has is you can just prototype a lot easier. It's just easier to validate your idea... having all these tools to

> actually make stuff physical helps a lot... And then also, if people doubt stuff, there's been times when... there's an idea that I think is cool, but some people don't see the merit in it. Just make a prototype and just bring it in, and then kind of pick the conversation back up from there. I've done that before. I think just communicating in general, they help for.

He also described that "if you have the right equipment, you can try more things out, or try riskier things", which meant that the ability to test frequently allows for additional exploration of the design space.

On the other hand, when P6 had more limited access to tangible design resources, such as people to offload work to and conduct analysis more thoroughly, he relied more on intuition instead of detailed engineering analysis:

> There are times that, especially when it comes to doing that design work, that if we can't outsource it to somebody else within the organization, external to the organization, that design projects have to kind of get delayed or mitigated in some other fashion... maybe isn't the best approach, but a lot of times when those resources don't exist, but there are significant constraints in terms of maybe time or dollars for us to get something done, you have to kind of go with the least elegant yet the 'most likely to be successful' solution. There's been many times where if I have to design a fixture to do some testing, that if I don't have the ability to really sit down and kind of crunch the numbers and design it in the most appropriate fashion, that kind of just throw something together that is likely going to work, but does not for maybe all the cases. So you end up carrying extra risk in your design project because there's really no other way for you to do it.

Participants also described how funding and schedule constraints influenced their design methods. With limited funding, P11 described that significant investment into one design often hindered their ability to redesign, which is often described as a recommended practice for carrying out many procedures such as those for DFM [10]. Their inability to redesign did not always result in the best design outcomes:

> Since... a lot of money had already been put into a certain design when a certain issue came up, we couldn't redesign it. We instead had to tweak it to make it work, which didn't result in the best is not even the best design, but like it didn't always result in good things, but it was being the good enough.

Information gathering methods were also impacted by funding constraints, as participants described in the design scenario. P10 described the different types of methods he would use based on what the budget would allow:

> If there was enough budget, I would fly out there with my team and check it out. Otherwise, just look up, go on Google or Google Maps, whether it's satellite view or street view. Or if budget didn't allow for it...if the city or whoever is contracting you out to do it, you could probably just say, "Hey, could you take some photos of the park one afternoon for me?" And that would probably suffice.

Another notable result was that the source of the funding also impacted the design methods used for some participants. P2 described how his targeted level of concept refinement would change based on the type of organization that was funding his project:

> If the funding source is a grant, per se, a government entity, then I would look at the funding as a very fixed, very specific amount with no room for growth, no wiggle room. Whereas if it's a privately-funded entity with expectations of certain milestones or project completion, I would definitely be evaluating what's the potential for getting more funding down the road if needed, and that has influenced how aggressive I might get in some design features or how conservative I might need to be, conversely, if I know there's very fixed, very rigid funding.

3.4.1.2 Organizational Characteristics and Design Methods

Organizational Characteristics influenced design methods via four common avenues: through appropriate or inadequate team composition, the existence of organizational relationships, the organizational size, structure, and culture, and the workplace itself. Team composition often changed participants' approaches based on the expertise on the team or lack thereof. For the design scenario, P8 mentioned that trying to leverage the skill sets on his team would change his information gathering methods:

> The design environment would also involve team members. Depending on their experience level, they could be an expert in some of these things. And so my process of gathering information might change based on [what] they're able to own and develop. And any data, any of their support in crafting like a survey or, you know, something like that.

If the team included experts on specific topics, practitioners reported that they tended to rely on those internal expert opinions more often than their own opinion or external sources. For example, P10 described the benefits of having internal experts on the team:

> It's always nice when someone on your team is an expert in anything, just because it means you can go to them rather than going out. I feel like it's always easier to work with people in your team than outside your team, just because they're more immediately available.

Two participants also brought up the importance of the demographic diversity on a team and how that might influence methods and communication. For the design scenario, P1 mentioned that if their team tried to take more ethnographic approaches by experiencing the park themselves, they would be limited by their own experiences, especially if they didn't have children, people with different heights, or people with disabilities on the team. Additionally, P9 described a diverse team that includes many other women engineers, several people of different races and ethnicities, and people from different regions of the US and the world. This diversity added to a level of bonding and comfort within the team, in a way that she hadn't "felt intimidated by men that are engineers or senior", changing their communication dynamics. These changes in communication affect the amount and type of information that is available to the team, which in turn changes the team's decision-making process.

Another notable finding was the impact of organizational relationships on an individual's design methods. Specifically, all of the participants at large organizations described the importance of trying to work within existing supplier relationships. For example, P6 described actively trying to build projects around existing suppliers in order to avoid the red tape required for vetting and establishing a relationship with a new supplier, impacting both DFM methods and project scope:

> To get through the red tape of approving a new supplier is not worth it 99% of the time. So there are many projects where if we already have a business relationship with supplier X, I am going to build my project around that supplier because I just don't want to deal with a new supplier. It would take me months to get a new supplier approved in the system... So there are numerous projects where knowing that we have a supplier that is capable of delivering what we need, it may not be the best, but it's what we need and it's acceptable is enough for me to tailor many projects around to avoid the other headaches.

One participant from a small company, P2, also described the importance of established supplier relationships, especially considering supplier constraints that small organizations often face like minimum run sizes:

> I've carried suppliers kind of with me to multiple projects, multiple companies... I don't think I get any preferential treatment or anything, but it's more just whittling down. If you're a medical company, you want an extrusion, there's probably, I don't know hundreds of suppliers across the country. But knowing which ones can do a minimum run for $1200 bucks, and get it to you in eight days, having a shortlist of whittled down to the most effective for what you need has definitely sped things up.

Organizational size, structure, and culture and their interactions with each other also played a role in influencing design methods used. Participants in large organizations reported having more organizational processes in place than participants in startups. For example, for documentation processes, P1 took on the additional task of documenting her work and past work due to a lack of existing documentation in her startup:

> That wasn't really in place when I joined and so it took a lot of time for me to familiarize myself with everything that had been done before me. And so, a lot of my work has also been making sure we have a living document that any future member would be able to reference and understand and be able to repeat.

In contrast, P9 had existing documentation on the project she could learn from while onboarding at her large organization:

> So when I joined definitely it was in its very early stages. it was a lot of learning through and getting up to speed with the process, the design process, but also the documentation. So there's a certain way in which we have a document repository.

Additionally, organizational culture and structure often influenced the frequency of communication within the organization and who practitioners engaged with for that communication based on the formality and level of collaboration of existing channels. Again, these influences on communication patterns can influence the team's overall decision-making process. P3 described how her company's collaborative and informal culture allowed for more frequent communication and feedback:

> In my company, it's just normal that people help each other out. So you can not right now because everybody's working from home, but usually you could just walk to somebody's desk and ask if they have a few minutes because you had a question for them. So you wouldn't have to set up an appointment and make it all formal, and people would just help you out period. So I think there is a lot of informal helping each other out, and as long as everybody helps each other, it kind of equilibrates and it's really a productive environment.

Similarly, P10 reported that he was more likely to actively communicate with his teammates due to his organization's collaborative culture compared to his previous experience in a more competitive and formal environment:

> At my previous workplace, there was a bunch of machismo going on. So I felt like there was definitely a pecking order, and like some people's ideas, you couldn't really refute. So in that setting, it's just picking your battles... [In my current environment] I'm more likely to just reach out to teammates, and I feel like I don't have to be as guarded. So in general, I feel like I can just ask dumber questions... and there's just more collaboration that goes on in general, and more transparency about things.

Another interesting result was that the workplace also influenced the design approach of P11:

> I think that's something I've seen with working at home. It just makes me [say], okay, I'm comfortable here. I'm in a more relaxed state of mind, so that translates for me directly into being a little bit less, I think not proactive, but less critical of the information I gather and less challenging of it and more likely to say this is good enough.

3.4.1.3 Market Characteristics and Design Methods

Within the Market Characteristics factors that emerged, legal and regulatory requirements had the most notable impact on practitioners' design methods. Participants described the need to fulfill documentation requirements that justify their design decisions in case they were audited by regulatory agencies. Additionally, P6 detailed how the costly requirements needed to get FDA clearance on a re-submission made him prioritize making design changes that did not require re-submission:

> The FDA gives kind of decision trees as to when you may or may not have to resubmit 510(K)s or do whatever else. So obviously, we adhere to those decision trees, but when you're looking at potential projects, especially if it's a modification of an existing project, a product, you're going to do whatever you can to make the design changes that don't require re-submission.

The strict regulatory requirements in the medical device industry also pushed the participants toward an emphasis on testing and validation. Several practitioners described an approach to testing that had the targeted goal of validation, or passing the test in a manner approved by the regulatory bodies. For example, P6 described the regulatory influence on what test methods he would even consider using:

> A big one that we always have to deal with is what is going to be accepted from a regulatory perspective. I can come up with crazy test methods to justify or to prove that a certain design change is viable and safe, but if the process to develop that test method is difficult to justify in front of the FDA, then obviously I can't utilize that.

3.4.2 Designer's Self

The internal Designer's Self factors that were found were organized into the following three categories:

- **Professional Self**: factors related to one's self as perceived in relation to a profession and one's membership of it
- **Internal Motivators**: intrinsic factors that influence an individual to undertake activities without external reward
- **Social Identities**: aspects of a person's self-concept based on their group memberships [72]

Complementing the Design Environment results, Table 3.7 shows the Designer's Self factors that emerged from the interviews, the definition of the factor, and an example quote demonstrating the factor. The factors are organized by the three categories described above.

Table 3.7: DESIGNER'S SELF FACTORS.

Factor	**Definition**	**Example Quote** (Participant ID)
PROFESSIONAL SELF		

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Table 3.7 – Continued from previous page

Factor	**Definition**	**Example Quote** (Participant ID)
Practice-based knowledge	Abilities based and developed through practice, expertise, and know-how gain [33]	"From as early as I could legally work... I was operating a Bridgeport milling machine for as long as I could remember. And so I have a very strong machining and hands-on background there as well. I grew up with it" (P6)
Education-based knowledge	Awareness of basic and specialized technical knowledge in design that compounds the formal education, and domain of technical and design language [33]	"I'm a mechanical engineer by training so the production and technical functionality... this is where I come from. This is where I got my university training" (P3)
Learning style	The way an individual learns (i.e.-by seeing and hearing; reflecting and acting; drawing analogies) [63]	"And so, because I am not really an auditory learner, I had to write it all down, and then write down why it wouldn't work. So I have a record of the stuff that wasn't going to work" (P4)
Confidence	Certitude of own personal abilities and professional competencies [33]	"I don't feel like I have much confidence in being an engineer and I still feel uncomfortable even calling myself an engineer... because I feel like I don't have a lot of experience" (P1)
Cognitive abilities	Capacity to think 'designerly'; understanding the nature of the problem to be solved; developing a distinct way of thinking about the problem and solution spaces; demonstrating a high level of abstraction for idea generation and evaluation rounds [33]	"While my role is mechanical engineer, I try to take on more human-centered designy stuff… And part of the reason why I do is because I feel in general, that kind of stuff isn't in conventional engineering curriculums, so I feel like it's typically a weak spot for engineers. So, especially for that reason, I try to step in" (P10)

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Table 3.7 – Continued from previous page

Factor	**Definition**	**Example Quote** (Participant ID)
Interpersonal communication	Awareness of communication ability in order to make public presentations, set collaborations, establishing rapport, and to communicate among a team [33]	"You have to learn how to present and talk to people. I don't think it's that true anymore for people around our age, because I think we're all much better at talking than whatever engineers came before us. But it is something that you have to think about is making sure that you're getting your ideas across and people understand what you're saying" (P4)
Managerial competency	Perceived competency for managing generic tasks, at a personal level and with colleagues or among the team [33]	"Generally with startups, managerial skills are really critical if it is a big project and you are bringing in a lot of consultants. I might prefer some managerial skills to in-depth electrical design expertise, for example, knowing where we can add resources and consultants in expert support. Then the critical thing becomes, well, how well can we manage those resources?" (P2)
Project management	Competence in developing and managing the project such as planning, progressing among the tasks and phases, and evaluating effectiveness and outcomes [33]	"I guess it's the methodology of how I work. And it's just the overall project management of looking at the big picture, but not staying there, of course, just identifying the little details… knowing where you're headed not only with the deliverables, with how much money we're trying to save definitely was giving me a clearer idea of setting what can we really achieve in that time? Where should we prioritize?... What can happen?" (P9)
Job role	Employment status and different work functions assumed in addition to being an active team member	"There's also a caveat where I'm a contractor and there are some full-time employees" & 'Part of my job is testing, but another part of my role is doing the fabrication" (P1)
INTERNAL MOTIVATORS		

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Table 3.7 – Continued from previous page

Factor	Definition	**Example Quote** (Participant ID)
Motivation	Engagement in an activity due to an inner perception of enjoyability and inherent interest and its association with a value outcome [33]	"I really love working with moms and babies and women's health. That's really my passion" (P1)
Personal ethics	An individual's level of ethical concerns and tolerance. Awareness and positioning of possible environmental, social, health, or design life performative consequences, or lack of compliance with legislation [33]	"I have personal standards, like when it comes to ethics. As an engineer that, in particular, it comes to play when it comes to work safety… I could not work for a company that would just have their production in a lower-wage country and then also save on safety equipment for work safety" (P3)
Lived experience of the product domain	Having personal experiences related to the product or its use environment to draw from	"And then being a dog owner, I want to make sure that dogs can drink, too, out of this park, out of this water fountain. I don't have any kids, but I know some kids. I've got some little brothers. So keeping that in mind that there might be kids and adults using in this... From my own experience, water fountains can taste bad. So I always, in my mind, I think of rust" (P2)
SOCIAL IDENTITIES		
Ability status	A person's capabilities to engage in certain tasks or actions or participate in typical daily activities [62]	"I don't have a disability status, but my little sister does. She has cerebral palsy, a mild form of it. So I think when it comes to design, I want to think about making things as easy and intuitive as possible" (P4)

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Table 3.7 – Continued from previous page

Factor	Definition	**Example Quote** (Participant ID)
Accents and vernacular	A way of speaking typical of a particular group of people and especially of the natives or residents of a region [62]	"[The project is] involving voice, and what are the challenges in considering the accents of the speaker, so the person that's issuing the commands... I have the understanding of what it's like when Siri doesn't understand me. And I've had to force my accent to sound more American English" (P9)
Age	The period contemporary with a person's lifetime or with their active life [62]	"I'm the youngest person at the company by three or four years. So I think that's different. I'm definitely at the end of being a millennial or beginning of being a Gen Z" (P4)
Cultural norms related to identities	The norms that broader society or communities have or perceive around those identities	"For instance, specifically like water fountains, I don't know if it's just my family... we wouldn't use it because it seems dirty... if someone was like, "What do you want a water fountain to look like?" I would want it to look clean. And so, at least when I was growing up... it was like an ugly green color. And then this rusted-ish looking metal" (P4)
Education level	Level of formal education (degrees and fields)	"I have a bachelor's degree in mechanical engineering, focused on aerospace actually... I would say 50% of the time, there's this perpetual unspoken battle between the PhDs and the bachelor degree folks" (P6)
Race and ethnicity	Of or relating to large groups of people classed according to common racial, national, tribal, religious, linguistic, or cultural origin or background [62]	"It's just bringing also my own perspective as a Puerto Rican who's part of the States, but not really." (P9)
Gender identity	A person's internal sense of being male, female, some combination of male and female, or neither male nor female [62]	"When it comes to gender, there's obviously limitations to medical devices I could design, just due to personal experience, if they're intended for women... there's definitely an aspect of that where it's like, I know it may work for me, but I actually have no clue if this is convenient for a woman" (P6)

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Table 3.7 – Continued from previous page

Factor	**Definition**	**Example Quote** (Participant ID)
Identities different from user	Acknowledgement of differences between individual's specific or multiple identities and their end-users' identities	"It can be a privilege to be able to do some of these projects in that position... And that's already top of mind to me to be humble and vulnerable... so that those that you're working with that will have different socioeconomic status, race, ethnicity as well can feel comfortable with you in their environment and it can be similar or very different than you. And in those cases, they often were very different." (P8)
Language proficiency	Level of proficiency in specific languages	"Our products are sold globally. I speak one language, English" (P6)
Nationality	Membership of a particular nation [62]	"I think being Indian and growing up in India has just made me more cognizant of the various situations people live in" (P11)
Representation of identities	The representation and inclusivity of the individual's identities in the organization or team	"The whole team except for me and the other engineering intern were all men and they're all white and tall... I just kept thinking, "Whoa, did I get this job just because, I don't look like them?" (P1)
Socioeconomic status	The social standing or class of an individual or group, often measured as a combination of education, income and occupation [68]	"I grew up in a very poor, poor neighborhood" (P4)
Stature	The natural height of a person in an upright position [62]	"I'm below average height" (P4)
Geographical ties	Locations where people have lived and have had exposure	"I only lived in California in my life, so I don't know how designs would need to change for different types of weather too, and then how that would determine the materials that you would need as well" (P1)

3.4.2.1 Professional Self and Design Methods

Of the Professional Self factors that emerged, education-based and practice-based knowledge, confidence, and job role had the most pronounced influence on design methods. Knowledge, both from education and practice, was one of the most commonly cited factors related to Professional Self for influencing the design methods used by the participants. Two practitioners reported their tendency toward gaining their knowledge from practice more than education. Other practitioners described how both experiences influenced their appropriate decision-making for their medical device projects.

Practitioners shared that education-based knowledge was especially helpful for learning and applying human-centered design methods, such as using interviews and observations, (P1 and P10) and having the appropriate technical understanding related to device application (P3, P4, P5), which helped with communication (P7). P1 described how her course work emphasized the use of human-centered design methods to understand user needs:

> I guess talking to users and getting a lived experience is part of what I think was emphasized in some of the classes that I took and programs I've done, and just things I've read from designers. I also took a couple of classes on disability studies, and I think that I learned a lot about just how architecture so not accessible for a lot of individuals.

For P9, her education-based knowledge was closely tied to her practice-based knowledge because of her applied research projects during her PhD, which helped her develop industry-related skills such as project management.

Practice-based knowledge was more often cited for efficient decision-making based on familiarity with the device, organization's resources, and regulatory requirements as well as for learning from past mistakes, especially after seeing products through to production. For P4, learning from past mistakes resulted in using decision matrices to challenge design fixation:

> When I try to design and move forward in projects, I usually have three or four things that I'm thinking, and then I do a Pugh matrix and figure out which one makes the most sense. Because I've fallen into the trap before where you find something you like, and you just go for it without really considering the other options. So having all of that done beforehand made it really easy to move forward.

Participants also reported learning from practice about wording specifications for easy translation to validation requirements (P2) and changing designs to incorporate more standard parts for ease of manufacturing (P7). On the other hand, P5 and P8 described the potential benefits of having less practice-based knowledge than their teammates because of the opportunity to inject new methods or creative ideation sessions that have otherwise stagnated from long-term experience, as described by P8:

> I'm often new to these things and... working with people tremendously more experienced than myself. And so I've seen it as an advantage because... as being a young engineer to be

> okay with not knowing, asking a dumb question. I think it's been beneficial because like I mentioned earlier, even asking some of those dumb questions causes those that might be older, more experienced than myself to think about things in a different way... it might send out some new thoughts that just have stagnated because they haven't thought that way. They don't move on from that.

Another notable relationship was between confidence, which interacted with knowledge and other factors such as social identities, and design methods. Having more or less confidence reinforced the belief or doubt of the practitioner's own capability, which in one case impacted the participant's engagement in the design process. With less confidence even with a similar level of expertise as P8, P1 described speaking up less and following others' lead:

> I don't feel like I have much confidence in being an engineer and I still feel uncomfortable even calling myself an engineer, and I think that relates obviously to level of expertise because I feel like I don't have a lot of experience. If I'm being kind to myself, I feel like I do have actually a good amount of experience compared to my peers, but at the same time, I feel like there's so much more to learn. And when you work under other people who are so smart and just tackle problems just at the root of it and are just so efficient, I feel like it's really inspiring, but I feel like it also changes the way I approach things because I really will let them take the lead or follow their guidance, and I think it's important to follow the guidance of those running things... I feel like this relates a lot to just confidence and how much one will speak up in a project, anything."

Considering the intersectionality between knowledge, identities, and confidence, P4 used her practice-based knowledge to succeed in a project, which reinforced confidence in her engineering capabilities for herself and for those around her, which could impact future design communication:

> I'm really proud of [this project] because, again, I've only been at this company for a year, and it was on people's list for, "You're going to get a bonus if you figure it out." And no one was really able to figure it out. So the fact that [my female coworker] and I were able to do this in less than a year because we didn't get our materials until January... So getting material, testing it out, and having all this data on it. I'm just really proud of being able to figure this out for the company. And myself, for my own ego, you know?... ignoring everything else. And also the way that I dress, but ignoring all of that. I know what I'm doing.

The last notable finding within Professional Self was the connection between job role and design methods used. Six of the 7 participants in small companies reported having additional responsibilities than their formal job roles, which added to their opportunities to gain practice-based knowledge that subsequently influenced their design methods. For example, P7 noted that because he had a lot more job functions in his startup, he was able to see the product go through many design stages, which helped him learn how to implement more DFM techniques in the next product iteration:

> In a small company, naturally, you have a lot of informal job functions because it's small and you don't have a person [for each domain], and I liked this actually because it made me discover a lot of domains. What I liked also is you see all the stages of the product... And we feel like because we've seen the whole time-lapse, we make some decisions differently. A very concrete example is trying to choose as [many] standard parts as possible and as little specific parts in your product as possible in order to, for example, because standard parts are approved, are tested and you don't need to manufacture tools to make it.

For the design scenario, many participants assumed a contractor role versus being a full-time employee, which influenced their information gathering methods and their concept selection methods. For example, several participants described relying on asking the hiring party for information, as illustrated by P2:

> I'm picturing this as some city project, I guess I could be a contractor hired by the city... So I would be asking whoever hired me to do this. If they don't know, I would be contacting the city, or landowner, or whoever's running the park to find out... It seems to be the path of least resistance is to ask as opposed to starting to do my own independent research. I'm not sure how to go about that research. I would need to get plans for this park and I don't know if that's publicly available information.

Additionally, as a contractor, P6 described the method of providing options to the hiring party for them to make an external decision on the concept compared to him making decisions on his own project:

> I guess the pathway would ultimately be to weigh out all the scenarios and the possibilities and do the best you can of looking at the cost-benefit analysis and then proposing that back to your customer. And letting your customer choose because they're ultimately the ones who are paying you to do this.

3.4.2.2 Internal Motivators and Design Methods

Prominent Internal Motivators factors that influenced design methods were lived experience of the product domain and motivation. Practitioners that described having lived experiences of the product domain often considered specific requirements related to their own experiences and sometimes drew their design information more from their own experiences than from external sources. For example, in the design scenario, P4 acknowledged the possibility of her reliance on her own experiences if she were working on a park down the street compared to one she had never been to:

> I think if I were at that space, I feel like I would think I know what I'm talking about when I don't... If I'm being completely honest, I don't know if I would be as thorough in terms of a lot of that data. Because I feel like I would know ... if it was my park down the street, it's like, dogs go there sometimes. I don't need to see what's happening ... I would think I have a base

> of knowledge that I don't actually have because at the end of the day, it's still just me as one person experiencing this area. So I think that would be my challenge. And I would hope that I would take a step back and try to come at it as an impartial third party. Like never been here, never seen this approach, but I'm not necessarily sure that's true.

Motivation and personal ethics around safety also influenced the design methods practitioners used. P1 noted that her passion for working on women's health impacted her approach of making sure to prototype and test with actual end-users:

> I really love working with moms and babies and women's health. That's really my passion. And I think that effort had already been there to understand user needs before I joined the project, but that became an additional push, I think, in the past months since I've been a part of the project, trying to actually get the device onto mothers to see if it actually is comfortable.

Personal ethics came in often during risk analysis and concept selection, which also relates to the strict regulatory setting that the medical device industry sits within. P11 described how his team selected concepts using multivoting which showed how his teammate's risk tolerances were different from his own personal risk tolerance:

> I'm willing to show a little bit more risk. However... that was a different point of view from the other members in the team because... in terms of the risk side, some of my teammates and, again, this being a medical device, I think that's justified, were a little bit more risk-conscious. When there was a difference of opinion, I think we stated our cases but tended to go with the risk-conscious one just because they're a new medical device on the market so to be safe. That's where I respect [our company's] higher levels of integrity and ethics than even mine.

3.4.2.3 Social Identities and Design Methods

Social Identities and their intersectionality influenced the design approach participants used in three key ways: 1) having identities and cultural norms different from the users made participants rely on more user-centered design approaches 2) certain identities, such as education level, and cultural norms interacted directly with methods used, and 3) the lack of representation in the organization changed how some practitioners went about communicating around design.

Many participants described situations where their identities and related cultural norms were different from the user, which impacted their design process, especially around communication. A common example that was brought up by multiple participants was considering differences in cultural norms when creating graphics, instructions, or manuals. For example, P6 was aware of cultural differences in graphics due to other people's challenges with that issue:

> There are some things that wouldn't maybe be uncommon to use like certain verbiages, or certain types of instructions because in our culture it may be inappropriate to use that language

> or to show some pictograms in terms of how to use something. But that's not necessarily the case everywhere. And I haven't necessarily had that experience, but I know of people or projects where they've tried to use certain graphics to convey certain information, and just how that gets contextualized in a different culture in general, just may be different. And so the instructions don't necessarily get translated very well, because there's no verbiage to go against.

Additionally, several practitioners described trying to reduce their assumptions by gathering information from the users or people that share identities with the users or changing the design methods they used to account for the difference in identity. Practitioners described cases where they acknowledged differences in age, gender, ability status, socioeconomic status, and language proficiency between themselves and their end-users. For example, P6 explained that when working on a device that is used differently between men and women, he relies more on gathering information from on-site nurses who have helped women patients with the device, literature search, and interviews with prototypes with women users than relying on his own experience. Similarly, P7 described the challenges of designing products to relieve pain for people with disabilities without having that disability:

> When you have an ability status, you can't imagine because you don't have the disability. You can't imagine what the disability is like. So that's why I was very focused on the user. Actually, it's the hardest when you design medical parts and you don't have the disability. It's very hard to not feel yourself if the product will relieve you, or if it doesn't relieve you. So you have to go to someone who has [that] pain and you have to let [them] try your product. And so, yeah, I guess it's kind of the hardest part of the process of designing these kinds of products is not being able to feel the real value of the product.

For P11, having a different language proficiency than their potential end-users changed the information gathering methods he used:

> So in Senegal, they speak French. I do not. And that made me more likely to be on the observation side rather than the interview side, because interviews, when we used Google translate, flunky, took time, made people impatient.

Another interesting result was how identities and cultural norms interacted directly with the design methods participants used. For example, P6 described the emergence of his education level identity within a competitive dynamic between teams that consisted of mainly PhDs versus Bachelor degrees. This dynamic resulted in aiming for a targeted level of concept refinement in an unspoken competition to out-design the other team:

> The interesting one, I would say, is kind of education level. I have a bachelor's degree in mechanical engineering, focused on aerospace actually. I would say 50% of the time, there's

> this perpetual unspoken battle between the PhDs and the bachelor degree folks. . . and there's this perpetual competitiveness...I could safely say, I have fallen victim to that, where you know the design works, but it's not "elegant" enough, so you intentionally kind of spruce it up a little bit, add more bells and whistles on there, just to quiet the other side of the fence, if that makes sense.

Participants' cultures also affected their considerations for the design scenario. P3 defined requirements differently because Switzerland tends to have very different water fountains than in the US and the importance of historical conservation in public areas is prominent in much of European culture. P9 described that due to her Hispanic culture, she has a community-driven mindset, which played into her information gathering approach that emphasized learning not only from the hiring party but also from the community and what would be valuable to them:

> Through my previous projects, and also from my culture, understanding the people perspective... And knowing what's really valuable for that community is going to be a driver. And just also considering that aspect of the interviews... And, again, I kept it very broad probably, but not only the community, maybe people who are still involved in the project that are maybe... people who hire us for this project. So just also from them understanding if there's anything in particular that we need to consider, that's not just something written out there.

Both P4 and P9 also described having accents that they have had to actively modify to either be viewed as more professional or to engage successfully with a voice-recognition product. For P4, her accent impacted her perceived professionalism by others, which she countered by preparing for technical discussions:

> I'm from the South Central part of L.A. so I had to go to speech therapy twice to speak better... You're trying to teach someone to sound smarter and more technical, or whatever. That's not necessarily the right accent you want. So that was always, not a sore spot, but I am aware of it a lot, because people have told me that I come across as very unprofessional when I speak, which is fine. I'm over it now. But it's something I'm really cognizant of when I'm trying to talk about projects. I need to make sure I have all the technical words down before I want to talk about something, because I know at the first impression, they're not going to take me seriously.

For P9, her experience with her own accent in the US made her more cognizant of the variations in speech that can occur even within one region and influenced the design methods used to validate their voice-recognition software by including a design of experiments:

> With the current project... it's involving voice, and what are the challenges in considering the accents of the speaker, so the person that's issuing the commands. And I think just in general, I have the understanding of what it's like when Siri doesn't understand me. And I've had to force my accent to sound more American English. So just there, just having that

> perspective... And I think it's something that was known already because our company is pretty global and there's some people from China and India... [but] it's just bringing also my own perspective as a Puerto Rican who's part of the States, but not really. And so this is something that understanding where the difference is there and really how the device is going to work, or we've had to do a design of experiments to record different voice commands issued by different people. And so there is understanding, well, there's variations within the regions, but also in our country or the Spanish, the English is going to sound a little bit different. So I would say, yeah, definitely for those in mind, that's something that we've had to consider, and it's just bringing my own perspective of being a Hispanic.

Lastly for Social Identities, the representation of the participants' identities in mainstream, engineering, and organizational culture varied greatly between all participants, which influenced their design approaches. The most prominent discussions specifically surrounded the lack of representation for several participants, including P4 who described again how that influenced her need to speak deliberately and accurately in order to not misrepresent her identities:

> It's something that I didn't used to think about because it wasn't predominantly in my neighborhood, in my schools. I didn't know there were so many white people again I went to school. I just thought, at this point, everyone just had already intertwined that it was a culture shock for me. So you're in your classroom and you're just different from everybody. So it's important, again, to make sure that when I do speak and when I do say something it's right. Or well thought out and making sure I don't misrepresent the identity that I have which is really... Not annoying because you put that on yourself. It is something that, when I'm talking about stuff, it's very evident and prevalent in 'how am I going to come across?'

P4 also detailed how her own experiences with lack of representation influenced her implementation of many information gathering methods by including diverse voices:

> I think a lot of the times when I'm interacting with the world, I often think this was clearly made for not me. . . In terms of my methods, I have often seen that things are designed for one demographic. So I think it's really, really important to encapsulate as many demographics, backgrounds, whatever, as you possibly can, even if it seems as simple as a drinking fountain, we just don't know how other people interact with the same thing. Whether it be based on where they grew up or their culture or if they grew up thinking drinking fountains are dirty, they're never going to use it anyway.

> I think a lot of old data was gathered by old white guys. So it's always good to have a new perspective, new questions to get information from, things that people wouldn't consider. . . Just a bunch of different scenarios that in this day and age are so different. We're a different group of people. It may not be the same. Families aren't the same as they were even five or 10 years ago. So, I think it's always important to keep updating what's out there at least for yourself.

3.5 Discussion

The results from this study demonstrate that a number of designer context factors, in both the Design Environment and the Designer's Self, affect practitioners' selection and implementation of design methods. These findings build on existing engineering design literature that focuses heavily on user context, technical constraints, or the professional experiences of the designer, such as their knowledge or level of expertise, when considering design methods [11, 12, 19–21]. This study demonstrates that engineering design practitioners do consider many factors outside of just the quantitative and objective decision-making methods that are focused on in engineering design literature.

Notable results highlighted how designers changed their methods depending on their identities and cultural norms with respect to their users, their team, and themselves. This finding adds to the current literature that focuses mainly on the difference in identities between designers and their users in Engineering for Global Development Contexts [34, 35], by showcasing how practitioners' identities and cultural norms within their own setting can also influence design approaches. For example, in conjunction with practice-based versus education-based knowledge dynamics, competition between practitioners with different educational levels led to an "out-design" approach, while confidence related to identities influenced practitioners' comfort with engaging in more communicative methods such as brainstorming openly or asking "dumb questions".

Organizational relationships that were related to the supply chain were also found to impact design methods, which is supported in the literature [10, 22]. However, these findings showcased the extent to which practitioners shaped their projects around these existing relationships especially in large companies to avoid the process involved in getting new suppliers approved. In small companies, these relationships were equally important but for different reasons. Startups can have difficulty finding supply chain partners that can work with their small manufacturing quantities.

Additionally, the COVID-19 pandemic during which these interviews occurred was mentioned in reference to how it impacted other existing designer context factors, such as funding, workspace, access to tangible design resources, and cultural norms related to identities. For funding, some participants reported having less funding and needing to be extra frugal with their spending during their design process. For workspace and access to tangible design resources, most practitioners were working from home, which made it more difficult to communicate with their colleagues and access certain software or equipment. Now, practitioners reported needing to plan more by waiting until they have a list of questions before reaching out to colleagues or planning ahead for getting access to software or equipment in the office. Only P1 described how the pandemic highlighted her privilege for having a stable engineering job at such a young age and her appreciation of that privilege.

The interaction between Professional Self and Social Identities influenced design methods in a number of ways, which have been explored in limited ways in engineering design literature. For example, social identities such as race, ethnicity, accents, gender, and stature influenced the perceived professionalism and expertise of the practitioners by other people. For some people, the interaction was negative, where having a "Valley Girl" accent and using African American Vernacular English (AAVE) was deemed externally as unprofessional as occurred for P4. This social perception based on identities impacted the participant's Professional Self in that she spent extra effort in thinking through her thoughts and ideas around design before speaking up or bringing them to other people for feedback. For other practitioners, often those with less marginalized identities in engineering, their Social Identities positively impacted their Professional Self. For example, P11 described that being male and Indian, with the socially perceived expertise and knowledge that can come with those identities, might offset people's assumptions around his young age and assumed inexperience. P10 acknowledged that being a white male made him more comfortable in spaces than people with minority identities. This comfort influenced his information gathering methods since he wouldn't feel uncomfortable going into different spaces for design ethnography methods, as well as his daily communication with team members for brainstorming and discussion, where he felt comfortable speaking up and tried to counter this dynamic by giving space for those less heard to share out. Professionally, communication between team members and external stakeholders is key to design, as many activities, such as brainstorming, rely on sharing information for team-based work. In general, confidence was related to this interaction between Social Identities and Professional Self. The participants that shared moments of doubt of their own capabilities or knowledge were all participants who identified as women, including the female participant with the most design experience.

Additionally, almost all of the participants that described experiences related to lack of representation of identities were all minority races (in the United States) and women. P10 was the only male who explained that the experience of living in a different country that did not speak English made him more aware of language barriers that can exist in majority English-speaking countries. This finding relates to the impacts that representation of different social identities or a lack thereof can have on organizational culture and a practitioner's Professional Self in the workplace. These influences can therefore affect how practitioners with less representation in their teams adapt their design methods to account for that added dynamic.

Participants often brought up situations of considering their own identities when they were different from their users' identities. These considerations were often a result of practice-based knowledge gained from failures or previous negative outcomes of not considering the differences between their identities. Participants also often described socioeconomic status considerations in reference to their nation's socioeconomic status compared to the user nations' socioeconomic status instead of reflecting on their own individual socioeconomic status. These findings point to power imbalances and potential inequities related to many of these design situations. For example, many identities were only considered, usually for participants with majority identities, due to previous failures, which means cases where the design did not meet its expected outcomes. These negative outcomes provide learning experiences for the practitioners to improve and consider their identities but at the cost of negative design outcomes. Additionally, the consideration of the socioeconomic status of a nation, while an important consideration, may also be reflective of the potential power imbalances involved in design work: who designs versus who receives.

This study was an exploratory study that aimed to gather qualitative data around designer context factors in engineering design. However, because the study was limited to medical device design practitioners for evaluative purposes, these factors found are currently based on those considered by practitioners in the medical device industry and not necessarily those in other industries. To support transferability, the authors aimed to pull detailed and nuanced descriptions that can support similar exploration and application in other engineering design sectors.

Additionally, the interview data relied on practitioners' abilities to recall past experiences or their hypothetical responses to the design scenario. These responses may not necessarily be reflective of what the practitioners actually do in practice, but the authors tried to address this by incorporating 3 different approaches (each interview section) to gather the information.

Though the authors did try to seek out diverse identities, the majority of the participants have more Western identities and a relatively similar age range. Also, since the majority of participants were recruited via convenience sampling, there are threads of similarities between some participants such as location or being in a startup, though each participant still had a plethora of very different experiences to bring to the table.

Overall, the findings from this exploratory study showed the wide spectrum of designer context factors that can influence engineering design methods. In practice, engineering designers can use this work to support intentional selection and implementation of design methods, which leverage the strengths of their individual designer contexts and mitigate their weaknesses. By understanding the interactions between designer context, including the Design Environment and the Designer's Self, and the methods practitioners use, additional support can be provided for practitioners to engage in more appropriate design methods for their context in order to can achieve desired outcomes.

3.6 Conclusion

In conclusion, this study sought to explore the phenomenon of Designer Context and its influences on design methods by answering the following research questions through a qualitative study:

1. What factors of designer context do engineering design practitioners consider in practice?

Across the 11 participants in this study, they considered 14 factors related to the external Design Environment and 22 factors related to the internal Designer's Self. The Design Environment factors included those associated with Resource Allocation, such as funding and schedule constraints, Organizational Characteristics, such as organizational size and culture, and Market Characteristics, such as legal and regulatory requirements. The Designer's Self factors included those associated with the participant's Professional Self, such as practice-based knowledge, Internal Motivators, such as personal ethics, and Social Identities, such as race and age. These factors were considered in practice to varying degrees across the participants.

2. How do designer context factors relate to the design methods used by engineering design practitioners?

The results from this study showed a wide variety of ways that different designer context factors can influence not only certain design methods used by engineering design practitioners but also the overall project direction and scope. Design Environment factors often present themselves as external constraints or enablers set by other people in the organization or external stakeholders. Commonly considered factors such as funding constraints or schedule constraints can change what methods practitioners decide to use for information gathering or concept evaluation. For example, with limited funding and time, practitioners reported relying more on easily accessible secondary sources of data such as literature searches compared to conducting an empirical study with components of ethnographic research methods or consulting more external experts with access to more time and money. Additionally, practitioners might make more estimations or rely on their own experiences and intuition to evaluate concepts compared to testing a concept with a prototype and rigorous test setup with more time and money. Many of these factors can also make or break a design project or an individual's experience on a design project.

The Designer's Self factors often present themselves in design as influencing the communication that occurs around a design project or the methods used especially when Social Identities are different between the engineering designer and their users. For example, different Designer's Self factors such as Social Identities and Professional Self changed how open participants were with sharing early-stage thoughts, which can influence a brainstorming session which is important for generating ideas and thinking through problems and solutions. Having different identities than the users often influenced the types of information gathering methods that practitioners have used, usually by relying more heavily on user feedback constraining the methods to those in which they think they can use with fewer assumptions about the user. These factors also played a role in the participants' cognitive process when thinking about what potential design requirements should be considered and related elicitation methods.

3.6.1 Future Work

Future studies will build on this work in many ways. Further development of the designer context factors as seen in engineering design includes the investigation of factors in other engineering design fields as well as sampling from a more diverse group of practitioners. A deeper exploration of the many relationships between designer context factors and design methods will be conducted and added to the current novice/expert literature. Because the COVID-19 pandemic was not explicitly probed in this study, though some practitioners briefly described ways in which it impacted their work, a study investigating the pandemic's impacts on engineering design processes would also be a valuable addition to this body of work. Based on the results of these deeper investigations, tools will be developed and tested to see if they can facilitate reflective practices throughout a design process so engineers can make intentional decisions about the methods they use in order to mitigate negative or inequitable design outcomes. Further work will investigate other impacts on engineering design outcomes from designer context factors.

CHAPTER 4

Prototyping Methods and Constraints for Small-to-Medium Sized Enterprises in East Africa

This chapter was coauthored with Jesse Austin-Breneman and published in Development Engineering under the same title in 2018 [73].

4.1 Abstract

Prototyping is integral to the design process for all projects, but particularly for small and medium-sized enterprises (SMEs). In resource-constrained contexts, designers must operate under unique constraints and opportunities. This study investigates the methods, constraints, and impacts on design outcomes of prototyping in seven design and manufacturing SMEs in East Africa. Results from a site visit to a Rwandan partner company as well as interviews with the engineering teams of the other organizations are presented. Practitioners reported that the main intent of prototyping in this context is to develop functional prototypes with increasing fidelity through a highly iterative process. This process was limited by constraints to manufacturing inputs, capabilities, and modeling predictions. These constraints contributed to increases in the time and cost for each iteration. Thus, results indicate that there may be a mismatch between the highly iterative method chosen and the constraints of the operating context.

4.2 Introduction

The design of new products for resource-constrained settings is increasing dramatically due to growing access to global markets and local production advantages [74] . A wide range of entities, from small social enterprises to large multi-national companies, see resource-constrained settings as growth opportunities and therefore develop new products specifically for these markets [75].

However, manufacturing products in these settings can be difficult. Small and medium-sized enterprises (SMEs) make up a majority of the firms in these markets [76] and face unique labor, capital, and infrastructure constraints [77]. Enabling these firms to overcome these challenges and effectively design and manufacture their products could lead to greater product success and more economically sustainable development.

This study is based on industry partnerships with seven SMEs in Rwanda and Kenya. These relationships were formed to improve the understanding of the needs of emerging market manufacturing enterprises. During a site visit to one manufacturing SME, a renewable energy manufacturer in Rwanda, the partner identified the mismatch between their operating context and currently available manufacturing equipment as a key challenge. The Rwandan manufacturing inputs and environmental parameters, such as seasonal changes and sludge characteristics, differed greatly from the design requirements of current technology. Additionally, partners reported that the cost and performance requirements of an SME were not necessarily met by larger industrial-scale equipment. The practitioners at the seven partner organizations emphasized physical prototyping to validate actual performance in response to this issue. Based on observations made during the site visit and interview responses, improved prototyping strategies could have a significant positive impact on design outcomes. Practitioners reported that current prototyping methods encountered difficulties in the East African context, resulting in prototypes that were too expensive and took too long to produce. Building upon previous work by the authors [78], this study seeks to answer the following research questions:

1. What prototyping methods do practitioners in resource-constrained settings use?
2. What resource constraints impact the prototyping process in these settings?
3. What is the impact on design outcomes of the identified constraints?

To answer these questions, this study presents results from a site visit to a partner organization as well as interviews with practitioners throughout the engineering teams of seven manufacturing SMEs in East Africa.

4.3 Related Work

This study draws upon a rich body of work on prototyping to examine prototyping strategies for design and manufacturing SMEs in resource-constrained settings. Prototyping is the activity or process that leads to the creation of a prototype. Ulrich et al. define a prototype as "an approximation of a product along one or more aspects" [22]. This definition includes artifacts ranging from virtual prototypes such as computer-aided design (CAD) models and other simulations, to more traditional physical models. Researchers have considered three main areas of prototyping: the purpose of prototyping, strategies used for prototyping, constraints on prototyping, and the impact of prototyping strategies on design outcomes.

4.3.1 Purpose of Prototyping

The designer's intent in creating a prototype has been used by researchers to categorize prototyping activities. Some models use the stage of product development to define the purpose of the prototype [79]. For example, Ullman proposes four types of prototypes: proof-of-concept, proof-of-product, proof-of-process, and proof-of-production [80]. These categorizations assume that the prototype is for validation and verification of previous design decisions. In contrast, Ulrich et al. suggest four broader categories of prototype intent: learning, communication, integration, and milestones [22]. This typology allows for prototypes that are used as communication devices to other stakeholders in the product development process, or as exploratory devices to search the design space more widely. As understanding the motivation for prototyping is crucial to understanding future prototyping activities, this study will draw upon this area to examine differences in prototype intent in resource-constrained settings.

4.3.2 Prototyping Strategies

Design researchers have categorized prototyping strategies along several dimensions to guide how designers create their prototypes. One important dimension is simplicity, ranging from simple to complex and can be measured using part count. Yang found that part count can be related to fidelity, which is how close the prototype resembles the desired product [79, 81]. One user study found that when using high fidelity, physical prototypes, designers were more able to confidently assess whether an idea met the requirements. Low fidelity representations of the designs were found to be helpful for assessing functional requirements, but not manufacturing or geometric requirements [82].

In examining early-stage physical prototypes, Houde and Hill argue that prototypes can be classified as clarifying the design along three dimensions: role (or usability), look, and function [83]. Although a single prototype can be used to test multiple dimensions, design teams also often categorize prototypes into "works-like" and "looks-like" models [84]. Ulrich et al. compare prototypes along the focused to comprehensive dimension, with focused prototypes clarifying fewer attributes of the design than comprehensive [22].

Current literature also places prototypes on a spectrum from analytical or virtual to physical [22]. Virtual prototyping technologies such as solid modeling and computer-aided simulations are an integral part of engineering practice [85]. These can produce comprehensive, functional prototypes with low investments of time and cost [86]. One study explores virtual prototyping and virtual reality technology as a faster method to test products before investing in the development of physical prototypes for final verification [87]. Design literature has also embedded rapid prototyping as a strategy to create physical prototypes more quickly and cheaply than their earlier counterparts [88]. For exploratory prototypes, Ward et al. describe Toyota's strategy of concurrent versus iterative prototyping for producing a large number of divergent prototypes. This literature is used to inform the analysis of prototyping strategies used by the partner organizations [89].

4.3.3 Constraints on Prototyping

Around each set of design problems, there are constraints that affect the strategies designers decide to use. Onarheim uses the definition of design constraints as "explicit and/or tacit factors governing what the designer(s) must, should, can and cannot do; and what the output must, should, can and cannot be" [90]. These constraints include both resource limitations such as time, cost, and materials, and social or organizational limitations. Other constraints during the engineering design process might include working around varying manufacturing lead times and accommodating new processes into a company while working with existing products and components. Eckert et al. also mention cost and "availability of machine or human resources" as design constraints that typically affect artistic design domains [91]. Given the unique challenges faced by the industry partners in this setting, this literature will be used to further examine prototyping constraints.

4.3.4 Impact on Design Outcomes

Design researchers have examined how different prototyping strategies correlate with design outcomes. Verganti examined the role of prototypes in stimulating design team discussion [92]. Specifically, proof-of-concept prototypes and rapid prototyping have been found to be useful for collaborative problem-solving at any stage of the product development process [93]. Elverum and Welo found that prototypes were an effective means of persuasion between stakeholders in complex system design teams [94]. Other researchers have examined how prototypes can influence innovation or novelty [95]. For example, one study has shown how physical models can help reduce design fixation faced by designers [96]. Another study has demonstrated the use of prototypes for user interaction among innovative design teams [97]. Campbell et al. show that functional prototypes can be used to involve users in each stage of the design process. Different strategies also impact the time and cost of prototyping [88]. The prototyping strategy used to reach the designer's goal can impact the time and cost spent on building prototypes [82]. Another study has shown that taking a concurrent engineering approach helps speed up the product life cycle compared to a sequential approach [87]. This study builds upon this work to further examine the impact of certain prototyping strategies in different settings.

4.3.5 Design for Base of the Pyramid

Research into resource-constrained settings has demonstrated that new design methods are necessary [98, 99]. Prahalad developed the Base of the Pyramid (BoP) concept and identified emerging markets as a future growth area for new product development [75]. Donaldson examined the impact of unique operating conditions and differences in the user populations on the product development strategies used in less industrialized economies [77]. Previous work by the second author similarly found that micro-entrepreneurs in these contexts might require specific strategies to meet their needs [100]. One group of researchers explored a method of applying existing optimization techniques to the unique domain of design for the developing world [101]. Viswanathan and Sridharan used university-based projects in India to highlight how these types of problems change the concept development and prototyping process [102]. This literature has found that designing for user populations at the BoP is both important and requires new strategies. A growing body of work examines prototyping specifically in these resource-constrained settings. Hillgren et al. proposed prototyping with slow refinement and extensive user testing to encourage adaptability to local environments [103]. Schlecht and Yang suggested more novel ideas were found when resources, such as access to machine tools and raw materials, were constrained early in the design process [104]. Donaldson found prototyping iterations were focused on imitating existing products and were limited to "achieving passable functionality" [77]. This work is used to inform the study of prototyping methods and impacts on design outcomes in resource-constrained settings.

4.3.6 Research Gap

Design research on prototyping has focused on consumer-facing product design which typically has few constraints on resources for prototyping. Additionally, although it has been shown that design processes should change to account for differences at the BoP, many of the BoP studies are based on either student projects or projects that were not produced at scale. This study seeks to fill this gap in the understanding of prototyping methods by examining practitioner processes at design and manufacturing SMEs in resource-constrained settings.

4.4 Methodology

This research seeks to explore these questions using case studies from seven SMEs based in Rwanda and Kenya.

4.4.1 Case Study Selection

The seven SMEs were selected such that they all had three characteristics: 1) they produced and designed their product locally in Rwanda or Kenya, 2) they performed prototyping activities during the design of their product, and 3) were a small or medium-sized enterprise. The companies varied in their employee nationality. In Kenya, two of the SMEs were founded and run by local entrepreneurs and two had at least one United States expatriate member in their leadership and engineering team. In Rwanda, one of the three companies had expatriate employees. All of the companies were mainly composed of Rwandan or Kenyan employees. Profile summaries of the companies selected for this study are shown in Table 4.1.

Table 4.1: PROFILES OF CASE STUDY COMPANIES.

Company	Location	Number of Employees	Sector
A	Rwanda	29	Sanitation, Renewable Energy
B	Rwanda	6	Maker Space
C	Rwanda	25	Renewable Energy
D	Kenya	250	Sanitation
E	Kenya	160	Manufacturing
F	Kenya	4	Product Development
G	Kenya	106	Cookstoves

4.4.2 Site Visit

One company (Company A) takes the local city influent of human waste and converts it into renewable fuel to sell to industrial customers. This enterprise was chosen through an existing network as an initial partner because it is an SME in a resource-constrained setting with a more manufacturing process-based design focus.

A site visit to Company A's manufacturing plant was conducted in order to gain a more in-depth understanding of their manufacturing environment. The site visit occurred over ten days and consisted of observation of the manufacturing processes and the prototyping involved in improving these processes. The investigator attended engineering team meetings and met with operational staff. The engineering team and operational staff were asked to suggest areas in which improvement could have significant impact on process outcomes.

4.4.3 Practitioner Interviews

Based on the preliminary information gathered from the site visit to Company A, follow-up interviews were set up with the four engineering practitioners from Company A. Additional interviews were also set up with a lead practitioner at the six other SMEs that were chosen based on contact accessibility, size, type of work, and initial responsiveness to the investigator. These participants were chosen due to their engineering roles and corresponding prototyping experiences in a resource-constrained setting. Collectively, their responsibilities included designing, managing, and maintaining the manufacturing process. One semi-structured phone interview was conducted with each of the participants, focusing on their prototyping definitions, purposes, methods, and constraints. One of the interviews was unable to be fully completed due to the participant's schedule and company changes. Out of the ten participants interviewed, five participants have less than 5 years of work experience, one participant has 5–10 years of work experience, and three participants have over 10 years of work experience. One participant did not mention his length of personal work experience. Seven participants have educational degrees in various types of engineering and two of the locals have degrees outside of engineering with self-taught engineering skills. One local participant's educational background was not recorded but has been working as a director in the family-run engineering business.

Each practitioner was interviewed individually for approximately 1 hour using Wi-Fi calling (FaceTime Audio and Skype) between the researcher in the United States and the practitioner. The calls were audio-recorded with consent. The interview protocol was structured with an introduction followed by background including past experience and current roles. During the background section, the participants were asked about their definition of a prototype in order to understand each participant's interpretation of the word. Then, the practitioners were asked to describe a recent design and prototype, including important principles in prototyping for their company. An overview of the interview protocol and example questions is included in Table 4.2. If time or experience permitted, the participant was also asked about earlier prototypes and about prototyping characteristics and methods used as a practitioner in a highly-industrialized setting.

The audio-recorded interviews were transcribed and qualitatively coded. The coding system was based off of provisional topics from the results of the authors' initial research case and interview questions. Then each interview transcription was coded first by grouping individual statements from each interview into overall themes based on the provisional topics. Additional topics that emerged were created to group the interview statements into. Then the statements were sorted a few more times into subgroups based on patterns and subthemes, pairing the specific quotes from the interviews with the overall message of the quote. The interviews were referenced several more times to verify the contexts of the statements to ensure more accuracy.

Table 4.2: INTERVIEW PROTOCOL OVERVIEW.

Theme	Example Questions
Introduction	• Purpose of the interview • Interview logistics
Background	• How long have you been working at the company? • What is your background and experience in engineering? • What is your experience with prototyping?
Describe Prototype Example	• Can you tell me about an early prototype you have developed for the company? • Can you give me an overview of the process? • What was the main goal that you started with in creating this prototype? • Would you say it is a simple or complicated design? • How many iterations of your prototype did you create? • What materials and supplies did you use and have access to?

4.5 Results

The following results collect the main themes gathered from observations during the site visit and interviews with the practitioners at the participating SMEs. The findings include the purpose of the practitioners when prototyping, the prototyping strategies used to meet that design intent, the constraints that limit the prototyping process, and the impact of those constraints on design outcomes. Six participants defined prototyping to be the development of concepts into inexpensive or small-scale models to predict the behavior of the full-scale, full-cost product. Three participants also defined prototyping as testing the assumptions and feasibility of concepts. One participant defined prototyping as the transfer of an idea into a real, tangible product.

Each engineer described at least one prototype example he or she developed or helped produce in Rwanda or Kenya. Some examples of these prototypes are low-cost manual presses and dyes, a cookstove, a briquette-making machine, and a handcart. Fig. 4.1 shows two examples of the described prototypes. The participant from Company E solely acted as a fabricator working with the client who was in charge of the design of the prototype.

The materials used for these prototypes include wood, mesh, silicone, fiberglass, sheet metal,

(a) Waste transfer cart. [105]

(b) Anaerobic baffled reactor.

Figure 4.1: EXAMPLES OF STUDIED PROTOTYPES.

steel bars, and polyvinyl chloride (PVC) pipes. The fabrication methods for these prototypes included the use of hand tools, welding gun, water jets, surface-grinding equipment, CNC mills, manual lathes, and drill presses.

4.5.1 Prototyping Constraints

The most notable results were the common prototyping constraints reported by the practitioners: limited availability of materials, difficulty in finding materials and fabricators, limited access to finished goods for modification, variable quality of materials and fabrication, limited access to skilled expertise, and limitations of modeling predictions. The participant count for each of these constraints is shown in Table 4.3 and a detailed summary of the constraints sorted by SME location and participant nationality is shown in Table 4.4.

Table 4.3: KEY PROTOTYPING CONSTRAINTS AND COUNT.

Constraints	**Participant Count (out of 10)**
Difficulty in finding materials and fabricators	8
Limited availability of materials	7
Limited access to skilled expertise	7
Limitations of modeling predictions	6
Variable reliability of fabricators	4
Variable quality of raw materials	3
Limited access to finished goods for modification	3

Table 4.4: KEY CONSTRAINTS BY NATIONALITY AND LOCATION.

	RWANDA		**KENYA**	
U.S. EXPAT	*Constraints*	*Participant Count (n=4)*	*Constraints*	*Participant Count (n=2)*
	Difficulty in finding materials and fabricators	4	Difficulty in finding materials and fabricators	2
	Limited availability of materials	3	Limited availability of materials	1
	Limited access to skilled expertise	2	Limited access to skilled expertise	2
	Limitations of modeling predictions	3	Limitations of modeling predictions	2
	Variable reliability of fabricators	3		
	Variable quality of raw materials	1		
	Limited access to finished goods for modification	3		
LOCAL	*Constraints*	*Participant Count (n=2)*	*Constraints*	*Participant Count (n=2)*
	Difficulty in finding materials and fabricators	1	Difficulty in finding materials and fabricators	1
	Limited availability of materials	2	Limited availability of *specialized* materials	1
	Limited access to skilled expertise	1	Limited access to skilled expertise	2
	Limitations of modeling predictions	1		
			Variable reliability of fabricators	1
			Variable quality of raw materials	2

4.5.1.1 Constraints on prototyping inputs

The four key constraints reported on prototyping inputs were limited availability of materials, difficulty in finding materials, limited access to finished goods for modification, and variable quality of raw materials. The majority of participants who reported a limited availability of materials felt that common raw materials were not offered locally "on the shelf." However, in Kenya, two participants reported that common materials did exist in Nairobi but were difficult to find, but one of these practitioners reported that special materials such as certain metal alloys were not available locally.

If the correct materials were available, almost all of the practitioners regardless of nationality and location reported difficulty in finding materials. The other local Rwandan was not asked that question due to the early termination of the call, and the other local Kenyan who did not describe difficulty in finding materials was the manufacturer whose client identified locally available materials before designing the prototypes. This sourcing difficulty was attributed to the decentralized nature of the hardware districts in Kigali and Nairobi and the lack of centralized information. One participant said that more resources exist than are readily findable and finds himself "constrained by a lack of knowledge, not just by the inherent constraints" of the location. Each of these practitioners, including the locals, specified that finding materials was done "all by word of mouth and exploration," with which it takes time to build up a network of resources. One of the practitioners stated that searching for materials with one person in Kigali could take one month with one person or one week with four people and their extended networks.

Participants who reported limited access to finished goods for modification described the challenge of finding products they could buy locally to make changes to during their prototyping. One example of this was a practitioner who wanted to buy a cooler to start a prototype that needed a leak-proof container but had to weld sheet metal instead because he could not find a cooler on the shelf. Another participant mentioned that as much as 40% of his prototyping inputs were imported special items or finished goods such as a specific type of heater. If the imported finished good is equipment or a machine, an additional layer of vetting must be done to ensure that the machine can be shipped, trained in-house, and supported throughout its use in both Rwanda and Kenya. Several participants in both Rwanda and Kenya described issues with finding vendors that could or were willing to send an engineer for setup and training and to provide support to small companies in East Africa.

The three practitioners who reported variable quality of raw materials referred to the inconsistencies of materials when purchased, which added extra prototyping iterations to account for variable tolerances and added time in checking all raw materials for quality. For example, one of the participants mentioned that sheet metal sold in Kenya is "never exactly the dimension that they say it is" so he must adjust clearances and iterate until it works with the actual sheet metal dimensions.

4.5.1.2 Limited access to appropriate manufacturing capabilities

The key reported constraints related to access to manufacturing capabilities were the difficulty of finding fabricators and the variable reliability of external fabricators. Participants sent parts out to a local fabricator when they did not have in-house access to the appropriate machines or tools such as welding guns or hole saws. The difficulty of finding fabricators was reported to not only be due to the decentralized nature of information, but also because many local fabricators are reluctant to work on small-scale or one-off prototypes since their shops are tailored to larger-scale production specifically for the existing local industries. Often times, fabrication shops charged a much higher cost for fabricating prototypes because of the manufacturing changes that are required.

The reported constraint of variable reliability of external fabricators refers to the unexpected output between different fabricators. One participant mentioned, "the other thing that isn't as available is high level of precision when it comes to machining." Another practitioner reported that "it can take a while to find a good fabricator to work with" due to the variation in reliability and quality between fabrication shops that have the appropriate manufacturing capabilities. Another participant found it difficult to manage outsourced fabrication with long lead times and multiple iterations due to communication errors.

4.5.1.3 Limited access to skilled expertise

The majority of the practitioners, including both expat and local practitioners, reported limited access to local technical expertise for fabricators, machine operators, product designers, engineering, repairing, and advising. They reported that this constraint was due to the limited availability of specific training and educational programs for these skills because product development and these industries are new to East Africa. The lack of skilled expertise in fabrication refers to the use of CNC machines and assessment of technical drawings. This constraint is attributed to the high price of equipment that makes it too expensive for schools to buy for students to learn on and the consistency of the current industries.

The participants address the lack of skilled expertise in mechanical design by training employees in critical analysis and operations. Training for product design and engineering can take any time from one month to six months according to one practitioner. However, during fast-paced prototyping, a Rwandan practitioner reported not always having that time to train his employees. Therefore, he tries to identify people with certain skills or quick learners first in order to spend less time with training.

4.5.1.4 Limitations of modeling predictions

The practitioners reported limited use of modeling and simulations, such as CAD, for product development because existing empirical models, standards, or simulations did not match well with their contexts or were too costly in terms of time and resources. The practitioners reported a lack of established literature or standards to inform any modeling methods. For several participants, access to modeling tools did not seem to add value because of the necessity of experimenting and prototyping manually anyway. For example, for one practitioner, "being able to play with it in person just felt a lot more intuitive than playing with it in CAD." Another participant stated, "Of course, my intention was to make people understand what I wanted them to understand. Luckily, they understood without the simulation." Additionally, the use of modeling is minimal because of the limited time the practitioners have to spend on learning the software and the added cost of simulation and modeling packages.

Another participant in Rwanda mentioned the necessity of better modeling tools to help with process decisions, and that designing "on paper" is different than in real-life context. One participant highlighted how modeling tools did not capture what materials are locally available and what will not be too costly to build in their context. Another issue mentioned was the difference in performance between the simulations based on manufacturing specifications and the actual performance of a purchased machine. This resulted in spending a lot of time trying to improve the machine to reach its originally expected performance level. This effort adds to the cost and potentially requires an investment in another machine.

4.5.1.5 SME and industry constraints

Characteristic of an SME, the practitioners had several ongoing priorities to oversee, so four of them in Rwanda and Kenya mentioned time split among other projects as another big factor in the time taken during their prototyping process. This limited bandwidth of the employees constrained the amount of support, time, and resources one company could put towards product development. One participant in Rwanda mentioned that “big organizations who have an RD team can just keep working on the idea, but for us, we just prioritize things, and prototyping comes last.” The participant also mentioned that the high cost of prototyping made it harder for him to prototype from scratch in the earlier days of the company because he had less capital. Prototyping projects had to be dropped midway or he had to modify finished goods until the company had enough money to do full prototyping projects from scratch. The later profits and income also allowed the company to hire more employees for prototyping and development. One local Kenyan practitioner also described costly support from the government due to high interest rates on loans at around 14–19% when procuring a machine from the United States.

For the social enterprise industries such as sanitation and cookstoves, the participants also attributed capital constraints to the nature of the industry. Many of the projects are often funded by grants or specific funders, which takes time to develop corresponding documentation and added stakeholders that must be convinced of the necessity of investing certain resources such as tools for prototyping. Two participants mentioned that testing of process steps and prototypes was sometimes dependent on external factors, such as weather and the local waste collection system, which added time and extra variables to the prototype testing. This is attributed to the nature of the sanitation business in resource-constrained settings. The local Kenyan manufacturer was also constrained by his client requirements. Regardless of the challenges, such as limited access to appropriate lab equipment or the testing facilities, the main client still required the product to be made to their specifications. The participant explained that these constraints from the client also help to improve their overall manufacturing processes and setup for future clients.

4.5.1.6 Other constraints

Participants also reported infrastructure constraints, such as access to cheap and reliable power. These constraints impacted the design and capabilities of the prototypes. In one case, a participant explained that manufacturers are constrained in location by where reliable supplies of electricity are provided. Buying land in these specified areas is expensive and drove this participant to create a more exploratory prototype to get around this constraint.

Another constraint was the lack of alternatives for equipment. For example, the participant from Company E had to make large investments in expensive machines, such as a laser cutter, that would meet his client's quality requirements, but the amounts these machines produced were well over the demand amounts in Kenya. He said the cost of equipment sometimes does not "justify the volume of products that are to be produced" but believes the investment will set the factory up for the future.

4.5.2 Prototyping Strategies

The most notable interview result for prototyping strategies was that all of the practitioners reported creating iterative, physical, works-like prototypes with increasing fidelity. Eight participants reported 2–6 iterations, one reported 22–23 iterations in trying to meet client standards, and another participant conducted 50 iterations. Each participant emphasized making physical prototypes due to the modeling constraints described previously. Several practitioners highlighted the importance of iterating quickly, referring to doing "quick and dirty" prototyping. The goal of this strategy as described by one participant is to "not over-invest in time and resources," especially since much of the time "you don't get things done in one iteration." Several of the practitioners reported "keeping it simple" by starting prototyping as cheaply as possible using readily available local resources, such as mild steel and in-house tooling, to determine if they could create the design effectively, such as a "five-dollar test" or a "very, very cheap on-the-fly version." One of the local Kenyan practitioners emphasized that the goal of simplicity is not due to the lack of resources, but rather is due to optimizing a product for function and cost.

If the simpler prototype did not work, the next iteration moved up in complexity, cost, or both until it achieved sufficient fidelity to validate the function of the desired product. One practitioner described an iteration of one prototype that was deemed unsuccessful and that project was dropped. Three participants found complexity in the process of prototyping as illustrated by this quote: "Where the complexity lies has always been in trying to make it as simple as possible while still performing certain functions."

One additional strategy reported by a practitioner was to increase usability of the design by including operational staff during prototyping. For example, one of the requirements was that the product should be repairable by the local staff. To do so, the "local staff should understand how it all goes together and be involved in the process" of prototyping. He also reported that drawing designs and having the prototype made in Europe and then brought over would not be ideal because the local staff would not be familiarized with that piece. Instead, they get the input of local staff to help out with final decisions and subsequent improvements due to their knowledge of the local resources.

Participants also modified these strategies to account for the constraints identified above. Two participants reported specifically planning for issues locating materials early on in the design process. One expat participant in Kenya described trying to make "parallel progress" when possible by planning the process so one can work on the materials issues "at the same time the prototype is being designed, built, tested, and market-tested." A Rwandan practitioner emphasized the importance of planning for local manufacturing capabilities for developing the prototype at the start of the design process during concept development.

4.5.3 Purpose of Prototyping

The following three key purposes of prototyping were reported: to test performance of the design, especially before scaling, to communicate with stakeholders, and to test the fabrication methods of the design. Eight participants reported using prototypes to test the performance of the design. This intent is typified by one response in which prototypes were used to "build a real-world example" at a smaller scale "to test if it would behave as you expect." Another practitioner reported that prototyping helps designers because "if they want to go big scale, then they know what to do and what not to do." Five participants also used prototypes to communicate with stakeholders, including investors, top management, customers, and clients. One participant described the goal of prototyping as reaching "the functionality that gives the client the confidence to invest in more expensive tooling for mass production." Two participants used prototyping to test the fabrication of the design, by asking questions on a process level, such as "what is the simplest, most cost-effective way I can make this given the numbers of whatever it is I wanted to produce?"

4.5.4 Impact on Design Outcomes

Overall, the constraints, especially in access to raw materials, added cost and time. The added cost was mainly due to shipping cost and taxes from importing materials that could not be found locally. For example, practitioners reported longer prototyping iterations due to full fabrication of the prototype in-house or longer sourcing time of an appropriate finished good from overseas as a result of limited access to finished goods for modification. One expat participant mentioned that common parts in the U.S. are not necessarily common in Rwanda, making the parts more expensive if they were found. Two of the expat participants also mentioned that being a foreigner adds to the difficulty of navigating the hardware district efficiently and cheaply due to the many sellers that gather around for attempted sales or sellers increasing the price for foreigners. The added time was mainly due to the time required to wait for the imported materials to arrive. In some cases, this may also involve expat employees bringing materials with them when they travel back and forth between the U.S. and East Africa.

Participants who had experience or exposure to resources for prototyping in the U.S. estimated that it would take on average 66% less time to create a similar prototype for the same application in the U.S. than it took them to prototype in East Africa. In making their estimations, the participants considered differences in contextual constraints such as the availability of supplies and fabrication shops, access to skilled expertise, and access to reliable electricity.

Three participants (two expats from Company A and one expat from Company D) also estimated the cost of creating their same prototype in the U.S. to be on average 39% more expensive than in East Africa, mainly due to access to better quality materials. However, two participants (expat from Company A and local from Company C) estimated the prototyping cost to be on average 47% cheaper in the U.S. than in East Africa, mainly because of access to local materials.

4.6 Discussion

Since each of the participant definitions of a prototype included the same overall scope including from sketches to full prototypes, the conclusions should not be skewed by different interpretations in the word "prototyping." One notable result from this study is that SMEs in East Africa are faced with unique constraints, which increase the cost and time required to produce effective prototypes. Similar constraints were reported between the participants in Rwanda and Kenya, regardless of whether or not they were U.S. expats or locals. Compared with SMEs in other markets such as the United States, these SMEs were constrained in their access to prototyping inputs, skilled expertise, and equipment and fabricators for prototyping. One main constraint faced in these contexts compared to the United States is that "most of these raw materials providers are not present online. It's not something that you can browse the Internet and find." While this practitioner associated the problem with access to online information, the true problem lies in the lack of both online and offline centralized information, such as catalogs. The challenge of finding special materials and sourcing them quickly is typified by this participant's quote: "In Rwanda, if I design something with a special bronze bushing, that might be a three-week delay trying to source that bronze bushing, where in the U.S. I can buy that with McMaster-Carr and have it the next day." This was true for both locally-run and expat companies in both Rwanda and Kenya, although to different degrees. Local companies reported more extensive networks to source available materials and fabricators and Kenya was reported to have a wider variety of input materials. However, all of the SMEs were working with a limited set of resources, and importing goods for prototyping consequently increased cost and schedule especially compared to the estimated time and cost for the same prototype in the U.S.

Having access to skilled fabricators and quality prototyping inputs is important due to the identified purpose for prototyping. The SMEs studied all shared the same overall purpose of validating the technical performance of designs within the context of Rwanda or Kenya. The engineering teams reported that predictions of performance from benchmarking existing machine equipment and from manufacturer specifications did not correlate well with observed performances. Additionally, practitioners relied heavily on small-scale functional physical prototypes because they did not believe existing virtual prototypes such as simulations or other models represented their operating context well. This may be due to a lack of relevant calibration data. This meant that prototyping was singularly focused on clarifying the design along the functional dimension [83] using a "works-like" model [84] and for the key purpose of learning [22]. Thus, constraints on the input materials and fabrication processes impacted prototyping outcomes significantly. In contrast, if the stated purpose was exploratory using low-fidelity models, the identified constraints would not have had as much of an impact.

Additionally, it is important to note the possible mismatch between strategy, constraints, and purpose. The "keeping it simple" strategy used by practitioners was composed of developing a series of simple, iterative physical prototypes. This was consistent with much of the prototyping literature [106]. Simplicity has been defined as lower part count, which leads to the outcomes of having less to design, fabricate, test, assemble, and maintain [79]. In this study, subjects similarly defined "simple" as prototypes which were inexpensive, small-scale, and used locally available resources. The reported strategy starts with the cheapest possible prototype, iterating on complexity until the necessary fidelity to validate performance is achieved. Limitations on prototyping inputs, manufacturing capabilities, and modeling predictions all constrain the fidelity of a given prototype. Reaching a sufficient fidelity in the resource-constrained context required additional time and cost. It is possible that a different strategy, such as identifying the correct level of fidelity at the outset and performing less iterations would actually minimize the investment in resources for the desired outcomes. Some practitioner decisions, such as sourcing key components for a prototype externally, were geared towards improving the fidelity at minimal marginal cost and time.

It is also worth mentioning that several participants reported that the prototyping landscape in East Africa is evolving. Currently, engineering education is growing, though more so in the fields of electrical engineering and computer science than in hardware and mechanical engineering. One of the local Kenyan participants described, "It is kind of changing in this part of the world as well. There's a lot going on here - we have broadened the type of product development and required prototyping as we have learned how to do more ourselves and as we've become more aware of resources and as new resources become available." The participant also clarified, "I'd say a lot of people aren't that aware of the level of sophistication that exists here. Maybe it's for lack of exposure on their part, but, often, it's because, like I said before, there just isn't that much information here because it's not geared to a prototyping environment. There's a lot that can be done here." Another practitioner described the start-up landscape in Kenya: "they're geared towards electronics, and that kind of space, but there are a few... companies that are pure hardware RD out there in Nairobi, but we're all isolated in our own bubbles for some reason, either geographically or otherwise... We're just spread out and we're all doing similar things. We could help each other, but we just don't talk, which is strange." Sharing resources between companies could also be another strategy to address the knowledge constraint.

4.7 Conclusion

This study uses case studies to examine the prototyping strategies of practitioners in manufacturing SMEs in resource-constrained settings. The engineering teams from seven SMEs in Rwanda and Kenya were interviewed after a preliminary site visit to an SME in Rwanda. The study addressed the following research questions:

1. What prototyping methods do practitioners in resource-constrained settings use?

The study found that studied SMEs in East Africa develop functional prototypes with increasing fidelity to validate technical performance. The engineers created simple, small-scale physical prototypes and iterated until a sufficient fidelity was achieved. Practitioners also involved operational staff to address usability concerns, and sourced from other countries when appropriate local goods could not be found. The focus on physical prototypes relates to the practitioner perception that they can gather data from physically building and testing a prototype to validate functionality that would be harder to gather using existing virtual prototyping methods, due to constraints such as accessibility or learning time.

2. What resource constraints impact the prototyping process in these settings?

Participants reported the key constraints that bounded prototyping fidelity were the variance in prototyping inputs such as raw materials and finished goods, limited access to manufacturing capabilities including fabrication shops and appropriate tools, and the limited availability of valid modeling tools for predictions given their unique context.

3. What is the impact on design outcomes of the identified constraints?

These constraints resulted in added time and cost to the prototyping process in order to achieve the desired functionality of the prototype.

In conclusion, practitioners in SMEs in East Africa faced unique constraints compared to the United States, such as limited access to materials, manufacturing capabilities, and valid modeling tools, when prototyping. Their key prototyping strategy was iterating on simple prototypes until they reached a high-enough fidelity to estimate the function of the final product. The constraints faced during their prototyping process added to the cost and time of prototyping.

4.7.1 Limitations & Future Work

This study was limited by several factors. Focusing narrowly on Rwandan and Kenyan SMEs allowed for a more in-depth examination of the research questions, but the generalization of results to other contexts is limited. Future work will examine prototyping strategies in other resource-constrained settings. The chosen sample of companies may also not be representative because they were not randomly chosen and the study consisted of a small sample size. The study is also limited by variability in interview results. The semi-structured interviews focused on subject-identified prototypes, which may not be representative of all prototypes made by the organization. Also, the face-to-face nature of initial contact with respondents from Company A could have introduced bias into their responses when compared to other interviews. Inconsistent Internet affected calls with two of the engineers based in Rwanda, including two dropped calls during one interview and overall lag and spottiness. Repetition of words was commonly required and may have affected results.

In order to address the identified constraints and their impact on design outcomes, the authors will pursue two additional avenues for future work. The first is to develop modeling tools tailored more to the context in order to produce high fidelity virtual prototypes. The virtual prototypes, which are more time and cost-effective, can be used to inform what physical prototypes should be made. The second avenue is to change the prototyping method to be more suitable for this context. This method could include the involvement of operators in the design and prototyping process in order to reduce the time and cost at each iteration. The engineering team could also identify the necessary level of fidelity before prototyping, reducing the total number of iterations by focusing designer effort on achieving the targeted fidelity.

CHAPTER 5

The Stakeholder Agreement Metric (SAM): Quantifying Preference Agreement Between Product Stakeholders

This chapter was coauthored with Mojtaba Arezoomand, Marianna J. Coulentianos, Kowit Nambunmee, Richard Neitzel, Achyuta Adhvaryu, and Jesse Austin-Breneman and under "Revise and Resubmit" status for the Journal of Mechanical Design Special Issue: Selected Papers from IDETC 2020 under the same title.

5.1 Abstract

Go/no-go decisions require engineering design teams to evaluate whether a concept is worth further investment of resources. These decisions can be difficult when product success depends on multiple stakeholders in addition to the end-user. This study proposes the Stakeholder Agreement Metric (SAM) framework to estimate the level of agreement between stakeholder preferences via the distance between optimal designs calculated from a preference model derived from conjoint analysis. The framework was tested in an empirical case study describing the design and piloting of a hand tool for informal electronic waste workers in Thailand. Data from a follow-up assessment indicate the SAM estimate aligned with future metrics of stakeholder satisfaction. The case study also qualitatively compared SAM to the Analytical Hierarchy Process (AHP). Data collection issues with AHP illustrated some of the practical limitations of the framework. This study suggests that the SAM framework is a promising tool to further explore as a way to support designers making go/no-go decisions that involve multiple stakeholders. Further exploration should include additional case studies to investigate potential outcomes of different SAM values and comparing multiple stakeholder groups.

5.2 Introduction

Product design requires engineering teams to translate abstract customer needs into engineering specifications [22, 107]. To support new product development (NPD), researchers have developed a number of tools for mapping user needs and preferences to product attributes [10, 22, 107]. Prior work has demonstrated that product success can be dependent on the needs of a number of pertinent stakeholders, not just the target end-user [22, 77, 108]. This study therefore defines a stakeholder as any group or individual who may potentially impact product success.

In these situations, engineers must evaluate designs based on the preferences of multiple stakeholders [108]. For example, a toy designer should create an artifact which satisfies both the parent who buys the toy and the child who plays with it. The designer must identify a single design and evaluate if that product can sufficiently satisfy key stakeholders [77, 108]. Based on evaluations throughout the design process, designers and managers must make go/no-go decisions on whether to continue development of a product or to pause and gather more information [109]. These decisions can be difficult if key stakeholders have competing preferences or incentives. For example, Atkin et al. highlight a case where the misalignment of incentives between employers and employees within targeted firms resulted in a lack of adoption of an otherwise beneficial industrial product [110]. Therefore, understanding alignment between stakeholder preferences is critical to identifying potentially successful designs.

To this end, researchers have developed methods to assist engineers in considering multiple stakeholders during product design. These strategies include qualitative methods, such as stakeholder journey mapping and Customer Value Chain Analysis [77, 111] and quantitative methods, including multiple-criteria decision analysis methods like Analytical Hierarchy Process and multi-objective optimization [23, 112].

However, both method types have potential limitations when addressing tasks where different stakeholders have distinct product interactions and preferences. Qualitative methods rely on the designer's ability to synthesize competing preferences into a single product. Therefore, results can vary greatly depending on the designer's level of experience in accurately processing rich qualitative information from multiple stakeholder groups [10]. Quantitative methods are more robust to designer variance but pose additional challenges. Multi-objective design optimization produces a single "optimal" design with respect to multiple criteria from stakeholder groups. However, this does not give the designer insight into how different the stakeholders' preferences are from each other. If there are significant conflicts, the "optimal" product could possibly not satisfy any of the stakeholders. In contrast, AHP does give designers a tool for understanding how product alternatives compare based on multiple stakeholder preferences. However, the method relies on multiple levels of pair-wise evaluations by every stakeholder, requiring a large amount of survey data collection from each AHP participant.

This work is a prescriptive study that aims to aid the making of a go/no-go decision on a single product by defining the degree to which the preferences of multiple stakeholders agree. A framework is proposed for estimating the agreement in preferences for product attributes between multiple stakeholder groups by measuring the distance between their optimal designs in the design space. This "Stakeholder Agreement Metric" (SAM) is intended to support design teams in understanding similarities between stakeholder preferences in a quantified way. This method is in contrast to product design tasks in which product variants or compromise-products are used to address preference variation across an end-user population [113, 114]. The proposed SAM framework is introduced in Section 5.4. An empirical study to evaluate the utility of the SAM framework in the context of the design of a tool for electronic waste recyclers in Thailand is presented in Section 5.5.

5.3 Related Work

This work builds upon a rich body of literature on preference elicitation in engineering design. The study draws from several qualitative and quantitative tools commonly used by practitioners to take into account stakeholder preferences.

5.3.1 Qualitative Methods for Considering Multiple Stakeholders

Many user preference elicitation methods, including interviews, observations and focus groups, are highly qualitative because they allow the designers to gather rich, nuanced information around user preferences [22]. When considering multiple stakeholders, Donaldson et al. introduce Customer Value Chain Analysis (CVCA) to visually map important flows between stakeholders in order to identify priority stakeholders for the success of a specified business model [77]. Ortbal et al. introduce a tool that uses personas and journey mapping to understand the motivations and needs of all stakeholders [111]. Overall, qualitative tools are used to gain nuanced information about multiple stakeholders, but they often aid mainly in the identification and prioritization of stakeholders or rely on designer experience to accurately translate requirements into design decisions, which can be susceptible to human error and biases [10].

5.3.2 Quantitative Methods for Considering Multiple Stakeholders

One key research area in quantitative methods is multiple-criteria decision analysis (MCDA). This approach offers guidelines for integrating the evaluation of design options across multiple objectives. One MCDA method, analytical hierarchy process (AHP), was developed to address situations in which objectives represent multiple stakeholders [23, 115]. AHP has been utilized in engineering design literature for a wide breadth of applications including improving environmental performance of a product and solving redundancy allocation problems [116, 117]. However, AHP has a number of potential drawbacks in practice, including theoretical flaws in the aggregation of preferences. For example, newly-introduced alternatives can cause rank reversal of previously rated items leading to opposite results [118].

Other common MCDA approaches include multi-attribute utility theory, multi-objective optimization, simple additive weighting, and combining various MCDA approaches into one [23, 112]. This paper uses AHP as a baseline comparison for the proposed metric as both are intended to support a go/no-go decision of moving forward with one design alternative which is acceptable to multiple stakeholders.

5.3.3 Use of Preference Modeling for Design Decisions

In the growing research fields of Design for Market Systems (DMS) and Decision-Based Design (DBD), researchers have utilized market research techniques to understand customer preferences and model customer choice behavior. The two main techniques for modeling customer preferences in these areas are conjoint analysis and discrete choice analysis (DCA) [119, 120]. Although there is significant overlap between the two areas, in this paper conjoint analysis refers to traditional ranking or ratings-based methods, and DCA refers to choice-based methods. For example, Li and Azarm propose making design decisions using an explicit designer utility function constructed from organizational goals, such as profit and market share [121]. In this method, conjoint analysis is a tool to represent customer preference data by quantifying the relationship between the customer's choice in product alternative and the individual attribute levels of the product, which can be used to estimate product demand [121]. The demand model can then be integrated into a larger organizational utility function, such as profit.

While many researchers view DCA as an evolutionary improvement on conjoint for modeling a customer's purchasing decisions within DMS and DBD frameworks [122, 123], traditional ranking or ratings-based conjoint analysis continues to be a popular approach under certain conditions [113, 121, 124, 125]. For example, because DCA requires the designer to specify the exact choice set available to the customer, if the set of competing products in the choice set is large or unknown, conjoint analysis may perform better than DCA. Conjoint analysis may also require less survey responses per participant than DCA and resulting models can be easier to interpret directly. The proposed framework assumes that a designer seeking to estimate the level of stakeholder agreement has already identified the product opportunity. The empirical case study and framework presented in this paper use conjoint analysis to construct the stakeholder preference functions for these reasons. However, DCA can be used as an alternative depending on the information available and the organizational goals.

5.3.4 Research Gap

Many NPD processes map customer preferences to product attributes to guide design decision-making. In situations where the preferences of multiple stakeholders may impact product success, researchers have developed a number of techniques for evaluating potential conflicts between stakeholders. These methods are limited in their ability to estimate the magnitude of the similarities in preference between stakeholder groups for a single design. This paper seeks to fill this gap by proposing a Stakeholder Agreement Metric which quantifies the similarity between each stakeholder group's estimated optimal products. The SAM can be used to support a go/no-go decision on whether a single design can satisfy all stakeholder groups. Based on Blessing's Design Research Methodology, this paper presents a prescriptive study in which the intended "support" or tool is the SAM framework. The tool is preliminarily evaluated by examining the use of the framework based on data from the empirical case study [126]. The case study explores the use of AHP and the SAM framework to support the design of a tool for informal electronic waste workers in Thailand. Based on the study, the researchers seek to answer the following research questions:

1. Does the Stakeholder Agreement Metric estimate the level of agreement between multiple stakeholders?

2. How does the SAM framework compare to AHP for supporting design decisions involving multiple stakeholders with distinct product interactions?

5.4 Proposed SAM Framework

The proposed framework uses conjoint analysis-based optimization to quantify the estimated amount of agreement between multiple stakeholders on a single product. This framework is broken down into four main phases:

- I: Stakeholder & Attribute Identification. Identify key stakeholders for product success and identify the product attributes and levels to test.
- II: Conjoint Analysis Across Stakeholders. Conduct conjoint analysis with the determined attribute levels and similar participant numbers to model preferences as a utility function for each stakeholder group. The results of the conjoint analysis should include the estimation of the utility functions for the stakeholder groups based on conjoint analysis data.

III: Design Optimization for Stakeholder Groups. Find the optimal design for each stakeholder group based on maximizing each group's utility.

IV: Stakeholder Agreement Metric & Design Decision. Calculate the Stakeholder Agreement Metric between the optimal designs. The design team can determine what distance is appropriate for a design to satisfy each stakeholder group.

5.4.1 Phase I: Stakeholder & Attribute Identification.

Identify i key stakeholder groups that are the audience for a single product. There are many methods for identifying and prioritizing stakeholders, such as CVCA [77, 127]. Because homogeneity of preferences within a stakeholder group is a key assumption of the SAM framework, particular care must be taken in defining the stakeholder groupings such that this assumption is plausible.

Once key stakeholders are identified, focus can be turned to potential product attributes. Literature in DBD defines customer-desired product attributes, **A**, as attributes on which customers tend to base their product selections [121, 122]. Then, n key product attributes (**A**) are identified with respect to all stakeholder groups, where each attribute has up to m levels:

$$A = [a_1, a_2, ..., a_n]$$
$$a_n \in [l_1, 1_2, ..., l_m]$$

For example, a product could be defined by $n = 2$ attributes, price, and weight. Price (a_1) could have $m = 3$ levels ($5, $10, $15) and weight ($a_2$) could have 2 levels (20 lb and 30 lb). In this phase, attributes with real-valued ordinal levels should be normalized between 0 and 1 in order to make the linear utility model from conjoint analysis easier to interpret and not weighted toward attributes with larger scales.

5.4.2 Phase II: Conjoint Analysis Across Stakeholders.

Conjoint analysis can then be conducted for each stakeholder group based on the attributes and levels determined in Phase I. The components of the methodology for a conjoint analysis with example methods are as follows [128]:

1. Select a preference model (part-worth function model, mixed model).
2. Select data collection method (full-profile, subset of factors). If using the full-profile method, determine the construction of the stimulus set (fractional factorial design, random sampling from multi-variate distribution).
3. Determine stimulus presentation (physical, 3D model).

4. Select measurement scale for dependent variables, such as utility (rank order, rating scales, paired comparisons).

5. Choose estimation method (multiple regression, MONANOVA).

Depending on which conjoint methods are used, the utility function can take different forms. For instance, in the empirical study, ranking-based conjoint was used, and the rankings were converted to ratings. A linear regression model was then constructed relating product attributes to utility based on ratings. This analysis is repeated for each stakeholder group. For this type of case, the utility function, U, from the conjoint analysis for the ith stakeholder group would have this functional form:

$$U_i = \beta_{i,1}a_1 + \beta_{i,2}a_2 + ...\beta_{i,n}a_n \tag{5.1}$$

Depending on the amount and type of data collected, robustness checks can be made at this stage to validate the preference homogeneity assumption within a stakeholder group.

5.4.3 Phase III: Design Optimization for Stakeholder Groups.

For each stakeholder group i, an optimization problem is formulated to maximize the utility of the stakeholder group across potential product attributes $\mathbf{A}$. The solution to this problem, $A_{*,i}$, represents the optimal levels of each product attribute with respect to that stakeholder group:

$$\underset{A}{\text{maximize}} \quad U_i \rightarrow A_{*,i} \tag{5.2}$$

The optimal algorithm for solving the optimization problem depends on problem characteristics such as utility function type and variable type. For example, Sequential Quadratic Programming (SQP) is commonly used to solve constrained, continuous, and nonlinear optimization problem [129]. Designers should select the appropriate algorithm for their conditions.

5.4.4 Phase IV: SAM & Design Decision.

For any 2 stakeholder groups i and j, the Stakeholder Agreement Metric is defined as 1 minus the normalized distance between their respective optimal designs, ($A_{*,i}$ and $A_{*,j}$). For more than 2 stakeholder groups, the SAM is calculated for each pairwise combination.

Since product attributes may consist of ordinal and nominal variables, the distance between two optimal designs is calculated using a heterogeneous distance function from machine learning literature, the Heterogeneous Euclidean-Overlap Metric (HEOM) [130, 131]. The distance, d, between two values of a given attribute, a, is:

$$d_a(a_i, a_j) = \begin{cases} overlap(a_i, a_j) & \text{if } a \text{ is nominal} \\ diff(a_i, a_j) & \text{otherwise} \end{cases} \tag{5.3}$$

The function $overlap$ is defined as:

$$overlap(a_i, a_j) = \begin{cases} 0 & \text{if } a_i = a_j \\ 1 & \text{otherwise} \end{cases} \tag{5.4}$$

and the function $diff$ is the range-normalized difference between the two values:

$$\begin{aligned} diff(a_i, a_j) &= \frac{|(a_i - a_j)|}{range_a} \\ range_a &= max_a - min_a \end{aligned} \tag{5.5}$$

This function returns a difference, d_a, that can be used to calculate the overall distance, or the HEOM, between two vectors with potentially differing types of attribute values, where:

$$HEOM(A_{*,i}, A_{*,j}) = \sqrt{\sum_{p=1}^{n} d_a(a_{p,i}, a_{p,j})^2} \tag{5.6}$$

The HEOM gives the overall distance between two optimal designs. To enable comparison across situations, this value is then range-normalized by the maximum possible distance between designs. The maximum possible distance, $max(HEOM)$, is equal to the number of attributes, n, because the maximum heterogeneous distance between two designs for a single normalized attribute is 1. Therefore, the SAM can be determined as:

$$SAM = 1 - \frac{HEOM(A_{*,i}, A_{*,j})}{n} \tag{5.7}$$

The SAM can be used to support design decisions when considering multiple stakeholders. Table 5.1 shows an example of how go/no-go decisions could be made based on SAM results. The value of the metric that corresponds with "similarity" level depends on the firm's situation and problem definition. The SAM framework can also be used to identify agreement between 2 stakeholders or 3+ stakeholders. The empirical study explores the SAM framework for the simple case of 2 stakeholders. However, for 3+ stakeholders, the framework can be applied to calculate pairwise agreement between stakeholders in order to identify which stakeholder groups may need more attention due to differences in preferences. The SAM framework could also be used to map a proposed design in the design space and calculate the agreement distance between each stakeholder group and that proposed design. This approach could allow designers to identify which stakeholders might be satisfied or dissatisfied with a proposed solution, and evaluation can be done around stakeholder prioritization and attribute prioritization.

Table 5.1: DECISION-MAKING EXAMPLE.

SAM Result	Example Decision
"Similar" along:	
All attributes	Go
Some attributes	Go, if clear prioritization of attributes that are similar
	No-Go, if more information is needed (revisit attributes and stakeholder needs)
Few attributes	No-Go

5.4.5 AHP vs. SAM Framework

In this paper, the SAM framework is compared to AHP due to the use of AHP to support go/no-go decisions of a single product with multiple stakeholders. For AHP, participants rank criteria from 1 (equally as important) to 9 (one criterion is extremely more important) in pairwise comparisons to understand how the criteria are weighted. In Step 2, the participants make pairwise comparisons between the design alternatives by rating them on each criterion, which results in local scores for each alternative. Step 3 then entails using weighted summation of the local scores of each alternative using the criteria weights to result in the global scores for each of the design alternatives. Figure 5.1 shows the processes for AHP and the proposed SAM framework.

5.5 Empirical Case Study

5.5.1 Project Context

Through a public health research partnership between the University of Michigan and Mae Fah Luang University in Thailand, the authors conducted an interdisciplinary needs assessment in 2017 to better understand the informal electronic waste (e-waste) sector in rural northeastern Thailand. E-waste recycling involves the dismantling of various electronics, including fans, washing machines, and CRT TVs, in order to retrieve and recover metals that the workers can sell for smelting. The informal e-waste sector is often less regulated, which includes little to no regulation of worker safety [132]. Therefore, the team's goal was to empower and enable e-waste workers to effectively dismantle e-waste in a cost-effective and safe manner. It is important to note that over the course

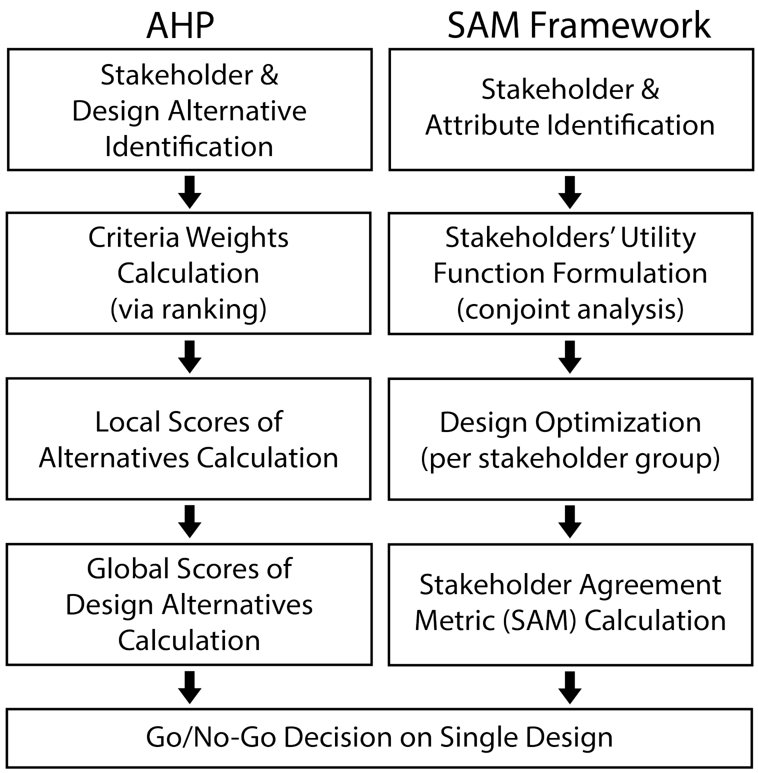


Figure 5.1: AHP STEPS VS. SAM FRAMEWORK.

of several years and multi-disciplinary discussions and workshops, this project is still currently being explored from a public health perspective, including work to further understand the working conditions of the e-waste workers and identifying additional modes of intervention.

One issue that the 2017 needs assessment revealed was that e-waste workers experienced increased hand injury risk during the common task of using a hammer and blade to split stators. As a small piece of the larger team, the engineering team focused on tackling this problem to explore opportunities at the workplace level. Figure 5.2 shows the task of splitting a stator and the tools currently used for general e-waste dismantling. A hand tool concept was selected through feedback on initial ideas from a small group of e-waste workers. By adding a handle and grip, the concept aimed to provide the user with more control when gripping the blade and to distance the user's hand from where the blade is hit by a hammer.

Conjoint analysis was conducted as a basis for the SAM framework, as well as AHP for comparison. The following sections present details of the implementation of the SAM framework and AHP for the hand tool concept. Data was also collected via an auction and an endline survey as part of a follow-up assessment of the intervention itself. This data was utilized for a preliminary evaluation of the SAM results.


(a) Tool used to cut stator.

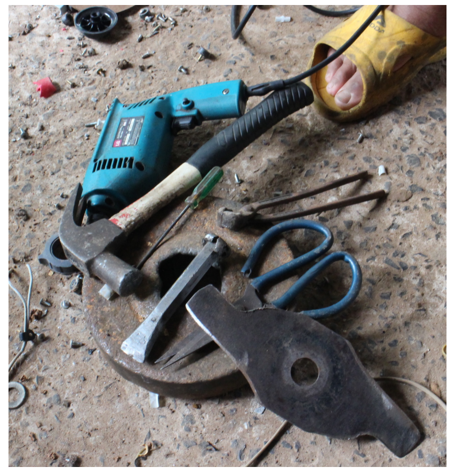

(b) Set of recycling tools.

Figure 5.2: TOOLS USED FOR DISMANTLING E-WASTE

5.5.2 SAM Framework

5.5.2.1 Phase I: Stakeholder & Attribute Identification

The needs assessment and survey results showed that the e-waste workers in Thailand were organized into informal e-waste firms of 2-5 people. These firms were organized into two roles: employers and employees, where most employers made e-waste income per quantity or weight of e-waste sold and most employees were paid by time, often per day. Although both groups participated in demanufacturing e-waste, employers performed additional tasks including: procuring scrap material, and maintaining a workspace for recycling by purchasing tools, protection equipment such as gloves, and organizing the area for recycling.

In a study of product adoption in Pakistan, Atkin et al. found that despite demonstrated economic advantages, an industrial product could still have low adoption within a firm due to differing incentives between employers and employees [110]. Due to the similar breakdown within the informal e-waste firms of employers and employees and their differences in pay incentives and work tasks, these two stakeholder groups were chosen for this framework. Observations from the needs analysis and survey suggested that individuals within each stakeholder group had similar objectives and therefore the assumption of preference homogeneity was plausible.

The attributes and levels considered in the conjoint analysis, shown in Table 5.2, were chosen based on benchmarking locally available tools, observations during the needs assessment, preliminary feedback during ideation, and the key design decisions that needed to be made. Price and blade length were numerical variables, while handle position, grip, and blade thickness were categorical variables.

Table 5.2: ATTRIBUTES WITH LEVELS.

Attributes (A)	Level 1	Level 2	Level 3	Level 4
Price	100 Baht	200 Baht	300 Baht	400 Baht
Blade Length	4	7	9	
Handle Position	Top	Side		
Grip	Yes	No		
Blade Thickness	Thin	Thick		

5.5.2.2 Phase II: Conjoint Analysis

Conjoint analysis was conducted with a user population of 85 e-waste workers, chosen through convenience sampling by Thai collaborators with existing relationships to the community. Of the 85 participants, 51 were employers and 34 were employees. A utility function for both groups was constructed based on the conjoint analysis data. Based on the process listed in Section 5.4.2, the following methods were used:

1. A part-worth function model was chosen as the utility model due to its simplicity, ease of interpretation, the categorical-type attributes, and the use of ratings for each profile.

2. Data collection was conducted using full-profiles of the designs in order to evaluate attribute combinations for the selected concept. The stimulus set was determined by full-factorial construction to allow participants to explore the entire design space, in this case, where the space was small.

3. The stimuli were presented as physical prototypes to allow participants to better visualize and understand the concept given potential translation errors. The conjoint analysis was conducted as a face-to-face survey with the physical prototypes (shown in Figure 5.3).

4. A rank-order measurement scale was used to collect more information in a shorter time, due to field constraints. While choice-based conjoint better mimics the reality of shopping, rankings save time by not requiring participants to choose from several different choice sets and also leads to a linear model that is easier to interpret once rankings are converted into rating scores.

5. Rankings were converted into ratings for each profile. Each stimulus set consisted of 5 total profiles for participants to rank. Each profile appeared in different sets and was ranked several times by the participants. Each participant ranked three stimulus sets. Ratings were

calculated by averaging over the rankings for each profile. With the linear part-worth function and ratings for each design profile, a multiple regression was performed to estimate the part-worth utility for the levels of each attribute.

(a) Full-profile prototypes. (b) Conjoint analysis in field.

Figure 5.3: CONJOINT ANALYSIS.

Because price and blade length were modeled as categorical variables, the model was able to capture some nonlinearities through a piecewise linear approximation. The presence of second-order interaction terms was checked, and the handle position*blade length term was significant. To model the categorical variables in a linear regression, dummy variables were introduced to the model. The following references were used for each dummy variable: blade length reference was 9 in., handle position reference was top, grip reference was no grip, and blade thickness reference was the thin blade.

The conjoint model was estimated using the method of least squares. The coefficients, standard errors, and p values for the employer and employee models are shown in Table 5.3. Price was removed due to the model results showing large insignificance for price. The data for price suggested that participants may have given their conjoint rankings without actually considering price, possibly due to the informal or unfamiliar display of price with each design alternative. The rest of the variables were included to gather more information on the variables for prediction and for use in the design optimization.

The significance of the F-statistics and the high adjusted R-squared results suggest that both models presented have high predictive power. Additionally, in order to determine if these preference models were different, another regression was run with participant role (employer/employee) as a predictor. The interaction terms of 4” blade*role and thin blade*role were significant with $p<0.05$, indicating that role influences user preferences for product attributes. However, there was insufficient data to validate the assumption of preference homogeneity within each stakeholder group. The presented model results show that for both employers and employees, their utilities would significantly increase with a grip and a side handle position compared to the top handle position. For both groups, a thin blade would significantly decrease their utility compared to a thick blade. For employers, the 4" blade would significantly decrease their utility, especially when changing the handle position from top to side. Employers also have a significant increase in their utility for a 7" blade with a side handle compared to a top handle. However, for employees, there is only a significant negative change in utility when going from top to side handle position for a 4" blade.

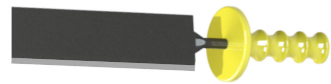
Table 5.3: CONJOINT MODEL RESULTS.

	Employer			Employee		
Covariates	Coefficient	Std. Error	P-value	Coefficient	Std. Error	P-value
C (intercept)	3.03	0.05	<2e-16	3.00	0.07	<2e-16
4in. Blade	-0.31	0.07	0.00	-0.06	0.10	0.57
7in. Blade	-0.02	0.07	0.82	-0.06	0.10	0.55
Side Handle	0.61	0.05	4.74e-10	0.61	0.07	3.70e-07
Grip	0.23	0.05	0.00	0.16	0.07	0.04
Thin Blade	-0.29	0.05	1.10e-05	-0.47	0.07	9.16e-06
Side*4in.	-0.33	0.07	0.00	-0.24	0.10	0.03
Side*7in.	0.18	0.07	0.01	0.06	0.10	0.59
	Adjusted R-squared: 0.93 $F_{7,16} = 42.48, p = 3.66e-09$			Adjusted R-squared: 0.83 $F_{7,16} = 17.27, p = 2.35e-06$		

5.5.2.3 Phase III: Design Optimization

Design optimization was conducted to maximize the utility functions for both employers and employees to find the optimal combination of attributes for each stakeholder group. The linear utility functions and linear constraints on the bounds of each variable result in a linear optimization problem, where the optimal solution always lies on the corners of the polygon of the feasible domain [133]. Due to the relatively small design space, in this case, a MATLAB code was implemented to go through all of the corner points to find the point with the highest utility. This process was repeated for the utility functions for both stakeholder groups. The optimal designs found for employers ($i = 1$) and employees ($i = 2$), translated from the dummy variables into the product attributes, a_n. are shown in Figure 5.4.

Employers’
Optimal Design ($A_{*,1}$) =



[7”,Side Handle, Grip, Thick]

Employees’
Optimal Design ($A_{*,2}$) =

[9”,Side Handle, Grip, Thick]

Figure 5.4: STAKEHOLDERS’ OPTIMAL DESIGNS.

5.5.2.4 Phase IV: SAM & Design Decision

To calculate the SAM, the $HEOM(A_{*,i}, A_{*,j})$ distance was calculated using Equations 5.3 - 5.6. Since the last three nominal attributes were the same between stakeholder groups, the $overlap$ function resulted in pairwise distances of 0. The $diff$ function was used to find the range-normalized difference for blade length:

$$diff(\text{blade length}_1, \text{blade length}_2) = \frac{|(7-9)|}{9-4} = \frac{2}{5} \tag{5.8}$$

The $HEOM$ distance was then calculated:

$$HEOM(A_{*,1}, A_{*,2}) = \sqrt{(\frac{2}{5}+0+0+0)^2} = \frac{2}{5} \tag{5.9}$$

Recall the maximum possible distance, $max(HEOM)$, is the same value as the number of attributes, n, due to the maximum range of each attribute through normalization and the distance function being 1. Therefore, the SAM was determined as:

$$SAM = 1 - \frac{HEOM(A_{*,i}, A_{*,j})}{\text{n attributes}} = 1 - \frac{\frac{2}{5}}{4} = 0.9 \tag{5.10}$$

Employers and employees were found to have an agreement value of 0.9, with optimal designs only differing along blade length, though both groups preferred longer blades. This SAM value indicates that in contrast to prior literature on employer/employee preferences in small manufacturing shops, these groups had general agreement on the preferred design.

The optimal results were brought to a local manufacturer in Bangkok to confirm how close a manufactured product could be made to the two optimal designs based on material and manufacturing constraints. The manufacturer produced hand tools with 8” long blades with some variability. The manufactured tool is shown in Figure 5.5.

Figure 5.5: MANUFACTURED TOOL.

5.5.3 AHP

AHP was also conducted with the same participants in order to compare the AHP global scores to the conjoint-based optimization results (Phase III of the SAM framework), given AHP's ability to consider multiple stakeholders' preferences of design alternatives [115]. The top four design alternatives from the conjoint analysis results were chosen for use in AHP. The study participants were first asked to rank the four prototypes from "most likely to buy" to "least likely to buy" in order to compare the AHP results with their rankings. For each step listed in Section 5.4.5, printed sheets (translated into Thai) were prepared to mitigate confusion and memorization and to allow participants to point when necessary.

In Step 1, participants made 6 pairwise rankings between the criteria of price, ease of use, durability, and safety, which were determined from the needs assessment. For the pairwise alternative comparisons in Step 2, participants were asked to point to which of the two alternatives they would prefer more based on each of the 4 criterion. However, during this step, the first 5 participants each stopped responding and became inattentive, so the field team decided to stop conducting AHP. Out of the 24 ranking evaluations required for this step, participants only completed 4, 8, 12, 12, and 16 rankings. In this case, the failure was likely due to survey fatigue which may have been from the many comparisons required for AHP, having already completed the rankings for the conjoint study previously, and participants having limited time for answering AHP questions in a setting where formal studies are not common.

5.5.4 Follow-up Assessment

In a follow-up assessment to evaluate the outcomes of the intervention itself, two metrics of the manufactured tool, willingness to pay (WTP) and usage status of the tool at 1 month, were measured among many other metrics for the overall multi-disciplinary study. The data from these two metrics were used also to evaluate the SAM's ability to estimate the level of agreement between both stakeholder groups.

Metric 1, the WTP of the manufactured tool, was determined by a Becker–DeGroot–Marschak

(BDM) auction [134]. In this auction, participants showed their WTP by bidding for the tool with fake money that was given to them to mimic a real world interaction. The money had value to purchase items including the tool and household items, such as sugar, cooking oil, laundry detergent, and snacks. The tool's price was randomly drawn, and if the participant's bid was above the price, then they received the tool. If the participant's bid was below the price, then they did not receive the tool and they paid nothing. Any excess money, if the price was drawn below the bid or if the participant did not receive the tool, was used to purchase household items. After a pilot test, the auction was conducted with 69 participants. Employers (n=38) had a WTP of 342.37, and employees (n=31) had a WTP of 360.13 out of a maximum of 500. A paired t-test resulted in a two-tailed p-value of 0.49, which means that the difference in the average bids between employers and employees was not statistically significant. Therefore, the WTP data suggests a non-significant difference between the groups.

Metric 2, usage status at 1 month, was based on the participants who received the tool. An endline survey was conducted with participants after 1 month of the distribution of the tools at the auction. Of the 54 participants that received the tool based on the auction results, 37 participants explicitly noted if they were still using the tool or not at this 1 month stage. The rest of the participants did not respond for various fieldwork reasons including that they did not have e-waste to dismantle in that 1 month. The 2x2 contingency table based on this data is shown in Table 5.4. Of the 15 users who stopped using the tool, eight reported the knife breaking at the weld while seven reported it was not suitable for required tasks, with four further specifying the tool was unsuitable because it was too thick. A Fisher's exact test on this data resulted in a two-tailed p-value of 0.1837. Both tests returned a null result, meaning a statistically significant difference between employers and employers for both metrics was not detected.

Table 5.4: METRIC 2 CONTINGENCY TABLE.

	Employers (n=19)	Employees (n=18)
Still Using Tool	9	13
Stopped Using Tool	10	5

5.6 Discussion

This paper proposes the SAM framework to quantify the estimated value of agreement between stakeholders' preferences of a design. The framework is applied to an empirical case study involving the design of a tool for dismantling e-waste in rural Thailand. In the case study, the calculated

SAM was found to align with the results from the follow-up assessment data. While the conjoint analysis indicated that stakeholder groups had significantly different preferences for some attributes, optimal designs for each preference model were similar, resulting in a calculated SAM of 0.9. Results from the follow-up assessment indicated satisfaction between the groups, shown by WTP and usage, were not significantly different. The similarity of the optimal designs may be explained by the overlap in product interactions and use cases between the two groups. Field observations showed that employers often recycled e-waste alongside employees in addition to conducting other owner-specific tasks.

In Atkins et al., the introduced manufacturing intervention was designed to minimize waste and increase profits, but inadvertently decreased throughput, especially during the initial learning stages. Although the employer greatly valued minimizing waste, subsequent assessment revealed that employees preferred interventions that increased throughput because of how they were compensated and the study measured low levels of adoption [110]. In this study, employers and employees also had differences in preferences for product attributes, which may have been due to factors such as different use cases, safety concerns or PPE used, but the optimal designs were similar, resulting in suggested similar levels of satisfaction between the two groups. It is also important to note that manufacturing quality control for the small batch of tools was not robust, resulting in broken knives for some participants before the usage metric was taken. Because the issue was equally likely to affect the accuracy of the usage metric for both stakeholder groups, the difference in agreement is unlikely to be biased by this mechanism. However, other evaluations of usage satisfaction including for those who did not receive the tool and continued to use the original blades may have given more insight into the usage metric of satisfaction.

This work also compares the support provided by AHP and SAM for go/no-go design decisions. One key difference is that AHP evaluates design alternatives and SAM is based on product attributes. AHP is therefore able to consider outside options, such as competitor products. SAM estimates preferences across variations of the identified concept only. This does not necessarily correlate with stakeholder preferences in a competitive market which includes options with different attributes. It is possible that the SAM framework could address this limitation by using DCA instead of conjoint analysis. The requirement for specific design alternatives in AHP also affects when in the design process it can be implemented. Since go/no-go decisions involve design teams deciding whether or not to invest further resources into a concept, estimating stakeholder preference differences may have more of an impact early in the product development process.

The case study also explored the difference between AHP and the SAM framework in practice. The evaluation of specific alternatives in AHP can limit the size of the design space searched, while conjoint analysis generates a utility function over the specified attribute space. The use of ranking-based surveys reduced the number of responses (3 rankings of sets of 5 tools) required from each individual for the conjoint analysis. In order to explore an equally-sized design space using alternatives for AHP, each participant would be required to give a much larger number of responses, 30 total rankings in this case. In the empirical case study, this may have contributed to participant survey fatigue. All participants surveyed for AHP terminated the survey during the alternatives evaluation section showing impatience with the process. The research team decided it would be unethical and counterproductive to continue the AHP survey after the first five participants failed to complete the questionnaire for the same reason. The surveys for SAM and AHP were conducted in the same order for logistical reasons, but a random ordering of both surveys per participant may have mitigated this issue. In different cases, participants may be more willing or able to complete the AHP questionnaire.

There are several limitations to the SAM framework as presented in this study. The use of optimized designs $A_{*,i}$ assumes that the stakeholder preference functions are smoothly varying over all product attribute dimensions. Highly nonlinear preference functions which are "peaky" only in a subset of dimensions could introduce significant error into the distance calculation which normalizes all dimensions to have equal weight. Additionally, the HEOM used to calculate the distance in the design space is a simplified metric which loses some information on categorical variables. Use of a different heterogeneous distance metric may improve performance of the framework.

In terms of the SAM framework as a tool, the generalized interpretation of the SAM has not been explored since it was only implemented for a single case. More cases are necessary to create guidelines for determining when stakeholders do not agree enough in the design space. Further validation conducted in a descriptive study-II (as described in [126]) must be conducted to determine robustness. Additionally, the SAM framework as implemented in this paper involves significant data collection to inform decisions around stakeholder groups, attributes, and conjoint analysis. While this amount of data allows for more detailed predictions of preferences, an organization's capacity to carry out this data collection may vary heavily depending on its resources and access to potential users.

5.7 Conclusion

Many engineering design methods that support the design of a single product while considering multiple stakeholders do not support designers in understanding how much each stakeholder group actually agrees or differs from one another. This paper introduces a framework to quantify a Stakeholder Agreement Metric (SAM). The SAM metric allows designers to estimate the similarities in preferences for product attributes between stakeholder groups by measuring the distance between their optimal designs in the design space. Having a way to quantify the level of agreement between stakeholders can support designers in making go/no-go decisions about moving forward with a single product where multiple stakeholders must be considered. Based on the results of the empirical study, the following answers to the research questions were determined:

1. Does the Stakeholder Agreement Metric estimate the level of agreement between multiple stakeholders?

   The results suggest that the metric does estimate the level of agreement between multiple stakeholders. A high SAM was calculated of 0.9. The willingness to pay for the manufactured tool and the usage of the tool at 1 month showed no significant difference between employers and employees, which is consistent with the high agreement value.

2. How does the SAM framework compare to AHP for supporting design decisions involving multiple stakeholders with distinct product interactions?

   The proposed SAM framework and AHP have a number of theoretical differences. AHP evaluates specific design alternatives, which may include outside design options, to determine the level of consensus for each alternative. In contrast, the SAM framework estimates stakeholder preferences based on product attributes and compares the level of similarity between "optimal" designs. This estimate does not evaluate outside options. In the empirical study, data collection issues prevented a full evaluation of AHP possibly due to the type or number of evaluations required for AHP.

5.7.1 Future Work

Future work includes a descriptive study-II [126] that further evaluates the proposed SAM framework as a design support, including the exploration of using the metric for other cases of design decisions, such as those involving more than two stakeholders and cases where stakeholders groups have a small agreement value. The current framework prescribes pairwise comparison, but the impact of potential aggregation methods will be investigated. Multiple utility function construction methods, such as DCA or conjoint analysis with choice-based surveys, will also be tested. Finally, the evaluation of the practical adoption and use of this framework by different types of organizations will be conducted to better understand the feasibility of data collection and analysis required for implementing the SAM framework in practice.

CHAPTER 6

Contributions, Implications, and Conclusions

6.1 Positionality Statement

This dissertation is influenced by my own positionality. Similar to the idea of designer context, my own researcher context impacted my work presented. As a Taiwanese-American woman who studied engineering in the United States, my race, ethnicity, and gender have been very salient identities in many situations where I was a visible minority in these identities. These experiences shaped my initial acknowledgment of the differences in identities that exist - an acknowledgment that many people with minority identities have faced and that many people with majority identities have not.

Two of my three research studies involved cross-cultural fieldwork in EGD situations. My original interest in these spaces stemmed from my impact-driven values shaped by my upbringing, family background, and social structures around me. However, I had the privilege through undergraduate university and my socioeconomic status to learn early on that trying to improve the quality of life across global locales as an American-based engineer often had undesirable outcomes. My own cross-cultural fieldwork during my PhD made many of these power and identity dynamics existent in these spaces very visible.

Throughout my graduate studies, my work at the University of Michigan's Ginsberg Center for Community Engagement also began to shape my reflexivity and understanding of our social identities and their role in creating power imbalances and inequities, especially between the University of Michigan and community organizations. I saw a parallel in my learning at Ginsberg and at the Center for Socially Engaged Design to my research on engineering design. In order to mitigate negative design outcomes, engineers also needed to reflect on their own identities, their own contexts when designing. My positionality on this idea pushed my research in the direction of designer context, in order to create space for and add weight to the idea that reflexivity in engineering design is necessary for achieving positive outcomes.

Chapter 3 was conducted for these very reasons. My positionality also influenced the methodology and results found in this study. For example, several practitioners agreed to participate in the study in order to contribute to student research or due to their own ties with the University of Michigan, which brings with it the issues of convenience sampling. My personal experiences in engineering and as a minority also shaped my interviews and the rapport I build with my interviewees. In some cases, my visible identities may have influenced the responses that the majority identity participants (i.e. - white males) may have given during the interviews. The data was also analyzed through my lens, including my own perspectives of social identities and the systemic structures in which we operate.

In 4, many practitioners were willing to help due to my student status. However, my US nationality and gender could have also influenced the information that was gathered and the behaviors of those I interacted with for the research during fieldwork and interviews, again due to the power dynamics representative of colonialism or the perception of women as non-threatening. For example, in Rwanda, I was called a "mzungu," which is used to refer to foreigners or white people. In this case, my gender and even my socially-constructed Asian race were not as salient as my association with being a foreigner, a Westerner, which reflects the prominence of colonialism.

In Chapter 5, only because of the expansive research done at the University of Michigan were we were able to join the cross-cultural public health project in the first place. However, the same legacies of research-based academic institutions also impact the methodology used for the research. Due to the funding structures of academia, the fieldwork was largely constrained by grant funding amounts and timelines. My role as a graduate student in mechanical engineering also largely shaped the methodology used in this study, including our proposed framework (i.e. - design optimization) and the comparative method of AHP. Additionally, this fieldwork could be reminiscent of colonialism that much of cross-cultural design falls into. However, we largely relied on our Thai partners to build trust and create a foundation for sustainable work, and my Taiwanese identity could have played a role in the rapport-building that occurred during the fieldwork in Thailand compared to my non-Asian colleagues, though the Thai language barrier still remained.

Overall, the framing of my research around designer context and their impacts on design methods is largely shaped by my own lens, experiences, values, and identities as well as those of my advisor and colleagues. The structure of academia encourages a research and publication-based approach to studies and fieldwork which influenced my study objectives and results. Additionally, funding constraints related to the structure of academia impacted all three studies and their implementation, which could have impacted the overall results and interpretations at which I arrived.

6.2 Summary of Findings & Contributions

This dissertation is comprised of three studies that demonstrated the influences of designer context on design method selection and implementation in different situations. Chapter 3 formalized designer context as an important concept to investigate in engineering design and illustrated how designer context factors impacted the design methods used by practitioners in the medical device industry. This study provided an initial foundation of 39 designer context factors that could be explored in future research and practice, especially as they pertain to design methods. These factors were broken down into those related to the Design Environment, or the external factors surrounding a designer when they are designing, and those related to the Designer's Self, or the internal factors related to a designer. Prominent Design Environment factors that impacted the design methods practitioners used included access to tangible design resources, supply chain constraints such as vetting suppliers, funding sources, legal and regulatory requirements, and team composition. Notable Designer's Self factors included practice-based knowledge, education-based knowledge, job role, personal experience related to the product, education level, language proficiency, and cultural norms related to social identities.

Chapter 4 described an example of how designer context arose in a study on prototyping strategies of design practitioners in small-to-medium sized enterprises (SMEs) in resource-constrained settings. This study uncovered what resource constraints practitioners in small organizations in Rwanda and Kenya faced that impacted the implementation of their chosen prototyping strategies and ultimately affected the time and cost required for their design processes. For example, the designers were working in a decentralized system of resources and stakeholders that impacted their ability to use their method of iterating on simple physical prototypes with increasing fidelity. Interestingly, the local practitioners spent time building and leveraging local, word-of-mouth networks in order to access these resources and stakeholders, while the US practitioners faced more difficult access and found makeshift ways to make their prototypes using the same approach, resulting in longer and more expensive prototyping processes. Together, these designer context factors including access to tangible design resources, organizational size, and nationality, impacted the efficiency of the designers' implementation of their selected prototyping method.

Chapter 5 described a prescriptive study that showed how designer context influenced methods in practice during an empirical study my team and I conducted in northeastern Thailand on the design of a tool intervention for electronic waste recyclers. This study proposed a design method for eliciting preferences from multiple stakeholders, the SAM framework, and compared it to the Analytical Hierarchy Process (AHP), an existing method. Throughout the implementation of these methods, our designer context influenced our process in several ways. Due to my design team's lack of language proficiency in Thai, we chose the conjoint analysis step in the SAM framework to be conducted using physical prototypes instead of nonphysical prototypes in order to reduce translation errors. However, due to the inherent setup of AHP, Thai participants were required to rank 4 criteria from 1 (equally as important) to 9 (one criterion is extremely more important) in pairwise comparisons with the criteria and the ranking descriptions all translated from English to Thai, during which the first 5 participants stopped participating in the AHP process. This outcome may have resulted from the design team's limited experience in the informal setting of the e-waste recyclers and the language barriers. The failure of AHP in our experiment led to our reliance on the SAM method to make a go/no-go decision on a design. These results also suggest that the SAM method may be a more appropriate method to use when designers have designer context factors that can negatively impact their ability to interpret data gathered from heavily spoken or written communication, such as limited appropriate language proficiency.

The designer context factors that were notably discussed across all three studies were supply chain constraints and practice-based knowledge. For supply chain constraints, participants in Chapter 3 mentioned constraints in vetting suppliers, conforming to existing supplier relationships, as well as changing the design for manufacturing and distribution requirements. Practitioners in Chapter 4 reported variable reliability of fabricators, similar to the need for vetting suppliers. The study in Chapter 5 faced similar issues around finding quality manufacturers. Having appropriate practice-based knowledge was important to work efficiently but also for choosing the right methods to implement that were appropriate to the designer context. For example, without having local knowledge or an extended time in the local setting, Chapters 4 and 5 impacted knowing what resources could even be accessed and how effective AHP turned out to be, respectively. The limited access to design resources seemed to be especially a problem for US expats living in Kenya or Rwanda, possibly due to their prescribed expectations of how to access resources. Several local practitioners explained that the resources existed, but to find them, one had to invest in building a network of stakeholders to find the best suppliers and resources via word of mouth.

The first two studies presented also showed the impacts of being a small organization and having limited access to tangible design resources. In both cases, practitioners at the small organizations tended to modify existing products instead of designing from scratch due to limited resources and funding. Limited tangible design resources also often affected the implementation of prototyping and testing methods for practitioners in small organizations, resulting in makeshift prototypes or testing setups that took more time to make and were less effective at answering the desired questions. Additionally, the first and third studies highlighted the cases of language proficiency and when that and other identities were different from the user. One participant in the first study described using observations instead of interviews when conducting a needs assessment in Senegal due to the language barrier, while another participant created a video to show what was going to happen in their study due to the differences in cultural norms. In the third presented study, our design team created physical prototypes and also tried to limit the text- and verbal-based communication in Thailand. Across the studies, social identities often only came up for designers when they had previous professional experiences, often past failures related to differing identities, or when they had personal experience with disenfranchised communities - either being a part of one or having relationships with people who are.

The factors that arose consistently across the three studies are consistent with those that have been most commonly mentioned in engineering design literature. For example, engineering design textbooks explain that supply chain vendors and partners have specific capabilities that must be understood, vetted, and when possible, leveraged by the designer [10, 22]. The findings from my research support this discussion and provides more detailed examples of how those supply chain constraints and enablers can impact design method selection and implementation. Additionally, a large body of work exists on the importance of practice-based knowledge for designers and their design activities [16, 19, 20]. The prominence of these two designer context factors in my work may be due to the common discussion of them in literature and in practice and vice versa. Figure 6.1 shows the list of factors found in Chapter 3. The factors that align with current engineering design literature on design methods, which focuses primarily on professional experience and manufacturing constraints for designer context, is shown highlighted in gray. The factors in bold represent those that emerged from Chapters 4 and 5.

Professional Self
- Practice-based knowledge
- Education-based knowledge
- Learning style
- Confidence
- Cognitive abilities
- Interpersonal communication
- Managerial competency
- Project management
- Job role

Internal Motivators
- Motivation
- Personal ethics
- Lived experience of the product domain

Social Identities
- Ability status
- Accents and vernacular
- Age
- **Cultural norms related to identities**
- Education level
- Race and ethnicity
- Gender identity
- **Identities different from user**
- **Language proficiency**
- **Nationality**
- Representation of identities
- Socioeconomic status
- Stature
- Geographical ties

Resource Allocation
- **Access to tangible design resources**
- Funding constraints
- Schedule constraints
- Priorities of management

Organizational Characteristics
- **Organizational size**
- Organizational structure
- Organizational culture
- Team composition
- Workspace
- Supply chain constraints and enablers
- Industry norms

Market Characteristics
- Legal and regulatory requirements
- Product reach

Figure 6.1: LIST OF FACTORS COMPARED TO LITERATURE.

My research also supports investigations into non-professional aspects of the Designer's Self, which aligns with literature from other design fields as well as specific design frameworks created in practice to push for positive social change and social justice [37, 38, 38–49, 56]. For example, Chapter 3 revealed the ways in which social identities can influence not only design method selection and implementation, but also other activities essential to design such as open communication with teammates and external stakeholders. Participants of color described how a lack of representation and diversity influenced the way they approached their design processes with their teammates. Several examples also emerged across all participants that showed the influences of acknowledging having identities different from their users. Studies 2 and 3 showed examples of how nationality and cultural norms of designers can influence the process and in some cases, can create dynamics that can severely change the outcomes of implementing certain methods, such as AHP.

The engineering design field is heavily situated in the idea of objectivity, neutrality, meritocracy, and depoliticization, which can in turn create design outcomes that perpetuate social inequities [31]. When literature in this field discusses aspects of the designer, it heavily focuses on professional aspects rooted in the broader engineering perception that the problem, technical constraints, and how skilled one is at engineering are the main considerations for achieving desired outcomes. However, this approach is limited by its exclusion of values and people, which are essential components to design activity. The results of my research suggest that a wide range of designer context factors can influence engineering design method selection and implementation, ultimately impacting the efficiency (time and resources used) and efficacy (achieved design outcomes) of design processes. Chapter 5 also brings up the question of how designer context may influence design method creation, in addition to selection and implementation. My work contributes to the existing literature in engineering design by providing a formalized view of designer context and expanding the considered factors past level of expertise or knowledge and supply chain constraints and by exploring how these factors influence design methods used. Through my research and findings, my work aims to open a parallel discussion of designer context to that around user context to support deep reflection on designer context and its influences on our practice, applying what many design practitioners in different fields have begun to discuss directly to engineering design research [57–59]. Figure 6.2 shows how my work (outlined) is situated in existing engineering design literature (gray) as related to factors to consider for design method selection and implementation.

This body of work suggests that socio-cultural norms in engineering design practice affect communication that occurs during the implementation of design methods. Methods used for information gathering, ideation, and concept selection, such as brainstorming or multivoting, would likely be amongst the methods that are most impacted through this mechanism due to their highly communicative nature. These studies showed socio-cultural norms to include designer context factors such as one's social identities, the representation of those identities around them, and the organizational culture in which they work. My findings also suggest that the extent and methods of gathering information on user context are mediated through one's designer context. For example, designers mainly discussed user context as relative to their own context. If their user context was different and therefore made their own context more salient, then practitioners often sought much

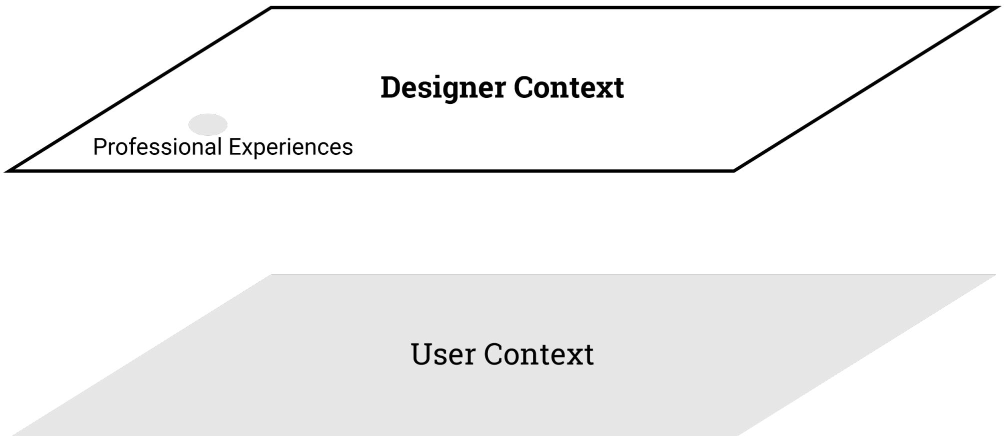


Figure 6.2: MY CONTRIBUTION TO ENGINEERING DESIGN LITERATURE FOR METHOD SELECTION AND IMPLEMENTATION.

more external information through a variety of information gathering methods. However, if the user context was similar to their own designer context, then they relied more on their own experiences and intuition to inform their decisions. Therefore, methods used to understand user context are not absolute and change based on one's designer context.

6.3 Implications

There are several implications of this work for engineering design practice and education. Much of the current focus in practice focuses on accounting for external Design Environment factors, while the main focus on Designer's Self lies in knowledge and expertise. The engineering design field has room to explore the potential impacts of embedding reflective processes on design activities and outcomes, especially around social and personal factors related to the Designer's Self. As further work on this topic develops, practitioners could benefit from the embedded use of reflective tools throughout their design processes that can help them make intentional decisions around design method selection and implementation and improve their design outcomes. Tools should support reflection around professional identity, personal motivation, social identities, and structural constraints and enablers in order to create intentionality behind practitioners' design decisions. These tools can be researched and developed to help practitioners understand what design methods may be better suited for their use based on their own context, access, and partiality. Building upon the act of reflection, interventions can also support designer recognition of power differentials between themselves and the communities their work impacts and ways for designers to challenge existing power differentials between their industry and the affected communities. These interventions would be especially important during cross-cultural design and fieldwork to support that design, as the power imbalance is often large in those situations, which can result in inappropriate design processes and ultimately undesirable design outcomes for both the designer and the communities at hand.

The ideal implications of this work in practice include the development and establishment of design practices that already create more equitable design processes than those that currently exist. If engineering design practitioners are able to inherently recognize and value different sources of knowledge, including those that are not traditionally seen as experts in the current social structures, and can understand their roles without overstepping boundaries, engineering design could have more equitable and positive design outcomes [135]. Additionally, this work provides an early look into the importance of diverse representation in engineering design teams that can influence subsequent generations of diverse engineering designers.

Implications for engineering education include the provision of oft-requested evidence for the need for reflection and analysis on our own selves in engineering design curriculum. This work can support the education of engineers that designer context does exist in engineering and does influence design practice and ultimately outcomes. Compared to other design fields such as art and design, human-computer interaction, and urban planning, engineering tends to seek objectivity and impartiality more frequently when teaching and viewing design processes, focusing mainly on gaining technical knowledge. Engineering education is growing in the form of emphasizing the importance of user-centered and human-centered design practices. However, in addition to this education, it is important for future engineers and designers to understand the role they play in how they approach a design problem. In order to achieve this, designer context can be applied to the student designers, the instructors as designers of courses and projects, and external partners as designers of student project contexts and priorities. This is an early start to creating more reflective engineering design practices that can lead to more equitable and appropriate design processes and outcomes.

This work supports several existing educational frameworks, including those from the Center for Socially Engaged Design (C-SED) at the University of Michigan, Creative Reaction Lab, Design School X, and other organizations that focus on equitable design such as Equity Meets Design and Reflex Design Collective. Many of these organizations provide their own educational frameworks for design that includes reflection and challenging of existing structures to achieve desirable design outcomes. For example, Creative Reaction Lab has an Equity-Centered Community Design framework that includes the steps of ideating approaches and inviting diverse co-creators, supplemented by a field guide that includes scenarios and reflective prompts [58]. Maya Goodwill developed A Social Designer's Field Guide to Power Literacy, which provides specific activities to help designers identify and mitigate power dynamics and imbalances [59]. Additionally, University of Michigan's C-SED is developing its own design process model and increasingly embedding it into engineering design curriculum, including the freshmen engineering course and the senior mechanical engineering capstone design course [57]. In conjunction with these engineering education frameworks and new process models, my work contributes to the reasons why the reflection of designer context is important in engineering design, even at the level of small technical subsystems as frequently taught in engineering curriculum. All of these individual subsystems that students might be working in would contribute to the broader design outcome of their products and have an influence on their end-users in practice. Additionally, students are often considering their next step in their professional career, and the findings of my work showed the impact that designer context can have on overall professional choices, which can in turn impact the diversity of the engineering design field across different industries. With more diverse representation in the field, this can increase the diversity of students that even consider engineering design to be a potential job option that can continue to feed this beneficial cycle.

6.4 Future Work

This dissertation provides an early step toward understanding how designer context influences design practice by exploring what designer context factors could be considered and their relationships to design method selection and implementation. Due to my research's exploratory nature, further work can be done to validate these findings and investigate the relationships presented here as well as additional relationships in more detail.

Further development on the appearance and definitions of these and additional factors should be conducted through studies of different engineering design fields, with large numbers of practitioners, and prescriptive studies of which ones should be more actively considered. These additional studies would help provide a broader and more substantial foundation for our understanding of what designer context can look like in engineering design, including a more thorough investigation into the structural social, environmental, and economic systems that influence all work.

Future work also includes a deeper investigation into particular relationships between designer context factors and design method selection and implementation. Similar to the existing work in novice/expert designers and their design activities, these comparisons can be conducted in a more targeted manner across many of the relationships identified through the studies presented in this dissertation.

Once an established foundation of literature detailing what designer context factors should be considered and how they can influence design methods, tools and interventions can be explored, developed, and tested to encourage active practitioner reflection around those designer context factors throughout design to support intentional design method selection and implementation that can result in more efficient design processes and improved design outcomes. One such existing tool that could be adapted is a Social Identity Wheel exercise that supports participants in acknowledging their social identities and understanding how they can influence their interactions with others.

Lastly, additional research can be done to explore how designer context manifests itself in other aspects of engineering design aside from design method selection and implementation. Some aspects that arose in my research include the relationships between designer context and the industry, companies, and work with which engineering designers decide to engage. The large impact on professional outcomes for each individual and ultimately different industries as a whole can be worth further investigation.

6.5 Conclusion

My dissertation contributes to the engineering design field by expanding our contextual considerations in design to include designer context, defined here as the Design Environment, or the external factors surrounding a designer when they are designing, and the Designer's Self, or the internal factors related to a designer. The importance of considering designer context is shown by presenting different cases in which designer context factors influence design method selection and implementation which impacts the overall efficiency (time and resources used) and efficacy (achieved design outcomes) of a design process. The studies presented showed different ways that designer context and its influence on design methods used manifested across different settings and industries in engineering design. This research provides a step toward developing an additional understanding of the connections between designer context and design practice and ultimately aims to support additional work to improve design processes and outcomes by embedding reflective practices and intentionality during design.

APPENDIX A

Definitions of Methods

Table A.1: DEFINITIONS OF METHODS FROM CHAPTER 3.

Method	Definition
INFORMATION GATHERING	
Company-centered information	Design information that can be obtained from within the company informally or formally [10]
Competitive benchmarking	Study of existing products with functionality similar to that of the product under development or to the subproblems on which the team is focused [10, 22]
Codes and standards	Specifically looking for existing codes and standards [10]
Customer complaints	Recorded by communications to a customer info dept. service center, third part websites, etc. [10]
Customer surveys	Surveying customers for information, feedback, etc. usually for redesign of existing products or new products that are well understood [10]
Design team's own experiences	Gathering information from the design team's experiences [10]
Document use environment	Record information, such as notes and pictures, about use environment and usage context around the product [69]
Engineering analysis	Applying principles of physics and engineering sciences to the task, such as engineering models, free-body diagrams, parameters estimation [10]
External expert consultation	Experts may include professionals at firms manufacturing related products, professional consultants, university faculty, technical representatives of suppliers [22]
Focus groups	A moderator facilitates a two-hour discussion with a group of 8 to 12 customers [22]
Internet search	Gathering information from the internet (i.e. - Google) [10]

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Table A.1 – Continued from previous page

Factor	Definition
Interviews	One or more development team members discuss needs with a single potential stakeholder at a time [10, 22]
Literature search	Published literature includes journals, conference proceedings, trade magazines, government reports, market, consumer, and product information, new product announcements [10, 22]
Observation	Watching customers use an existing product or perform a task for which a new product is intended can reveal important details about customer needs [10, 22]
Patent search	Patents are a rich and readily available source of technical information containing detailed drawings and explanations of how many products work [22]
STAKEHOLDER ANALYSIS	
Identify stakeholders	Identify the many different parties involved in delivering and financing care related to the need [69]
Prioritize stakeholders	Identifying key stakeholders to gather information from when several different groups of people can be considered the customer [69]
Stakeholder cost-benefit analysis	Evaluate the barriers that might cause a stakeholder to resist the adoption of a new innovation, as well as the benefits that may drive their adoption [69]
REQUIREMENTS DEVELOPMENT	
Define customer requirements	Clearly and intentionally interpret and define customer requirements to consider [10, 22]
Classify requirements	Identify the requirements that are most important to the success of the product in its target market and must ensure that those requirements are satisfied by the product [10]
IDEATION	
Brainstorming	Group technique that makes use of the broad experience and knowledge of groups of individuals through a non-threatening session of rapid, free-flowing ideas [10]
Checklist	Create checklists to remember important functions or tasks when ideating [10]

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Table A.1 – Continued from previous page

Factor	Definition
Implement (parts of) an existing solution	Aimed at finding existing solutions to both the overall problem and to the subproblems identified during problem clarification, including synetics techniques or analogoous inspiration [10, 22, 70]
Stimulate creative thinking	Additional approaches that encourage creativity and lateral thinking by removing perceptual, emotional, intellectual, and/or environmental blocks [10]
CONCEPT SELECTION	
Choosing the first concept in mind	Selecting the first concept that is thought of [22]
Decision matrices	The team rates each concept against prespecified selection criteria, which may be weighted (i.e. - Pugh matrices) [22]
External decision	Concepts are turned over to the customer, client, or some other external entity for selection [22]
Intuition	The concept is chosen by its feel - explicit criteria or trade-offs are not used [22]
Multivoting	Each member of the team votes for several concepts. Highest votes is selected [22]
Pros and cons	Team lists the strengths and weaknesses of each concept and makes a choice based upon group opinion [22]
Targeted concept refinement	Prioritizing a specific level of concept refinement to reach [22]
CONCEPT TESTING	
Bench testing	Testing of materials, methods, or functionality in a small-scale, controlled environment, such as on a laboratory workbench [69]
Determine test plans	The determination and prioritization of what tests to conduct and how to conduct them [10]
Prototype and test	The team builds and tests prototypes of each concept, making a selection based upon test data [22]
Simulated use testing	Various features or functions are tested as a system on an anatomical model or proxy [69]
Use of test standards	Utilizing generally agreed-upon set of procedures, criteria, dimension, materials or parts for test methods [10]

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Table A.1 – Continued from previous page

Factor	Definition
RISK ANALYSIS	
Functional design validation	Confirmation that the design specifications meet customer requirements [69]
Failure analysis	Determine causes of failure to strengthen the design [10]
Failure Mode Effects and Analysis (FMEA)	Team-based methodology used to identify the mode of failure of every component in a system and determines the effect on the system of each potential failure [10]
ADDITIONAL METHODS	
Design for Manufacture (DFM)	Series of procedures to consider all steps of production when making design decisions [10]
Design for Assembly (DFA)	Series of procedures to consider ease of assembly (handling, insertion, fastening, etc.) when making design decisions [10]
Consider distribution for design	Changing the design based on the supply chain constraints for shipping and distribution [10]
Provide clear work instructions	Providing clear instructions for assembly and/or manufacturing [10]
Documentation of approach	Creating an accessible and correct collection of information on all aspects of the design process [10]
Material selection	The processes involved in selecting material(s) for the design [10]
Concurrent engineering	Team members perform their jobs in an overlapping and concurrent manner so as to minimize the time for product development, as opposed to serially [10]

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