Chou, Suzanne; Austin-Breneman, Jesse

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Prototyping methods and constraints for small-to-medium sized enterprises in East Africa

Suzanne Chou, Jesse Austin-Breneman *

University of Michigan, 2350 Hayward St. Ann Arbor, MI 48109, USA

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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.

1. Introduction

The design of new products for resource-constrained settings is increasing dramatically due to growing access to global markets and local production advantages (Khanna and Palepu, 2010). 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 (Prahalad, 2009). 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 (OECD, 2000) and face unique labor, capital, and infrastructure constraints (Donaldson, 2006). 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 (Chou and Austin-Breneman, 2017), 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

* Corresponding author.
E-mail addresses: suzchou@umich.edu (S. Chou), jausbren@umich.edu (J. Austin-Breneman).

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throughout the engineering teams of seven manufacturing SMEs in East Africa.

2. 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 and Eppinger (2012) define a prototype as "an approximation of a product along one or more aspects." 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.

2.1. 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 (Yang, 2005). For example, Ullman (2009) proposes four types of prototypes: proof-of-concept, proof-of-product, proof-of-process, and proof-of-production. These categorizations assume that the prototype is for validation and verification of previous design decisions. In contrast, Ulrich and Eppinger (2012) suggest four broader categories of prototype intent: learning, communication, integration, and milestones. 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.

2.2. 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 (Yang, 2005; Rudd et al., 1996). 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 (Hannah et al., 2012).

In examining early-stage physical prototypes, Houde and Hill (1997) argue that prototypes can be classified as clarifying the design along three dimensions: role (or usability), look, and function. Although a single prototype can be used to test multiple dimensions, design teams also often categorize prototypes into "works-like" and "looks-like" models (Koo et al., 2014). Ulrich and Eppinger compare prototypes along the focused to comprehensive dimension, with focused prototypes clarifying fewer attributes of the design than comprehensive.

Current literature also place prototypes on a spectrum from analytical or virtual to physical (2012). Virtual prototyping technologies such as solid modeling and computer-aided simulations are an integral part of engineering practice (Rix et al., 2016). These can produce comprehensive, functional prototypes with low investments of time and cost (Camburn et al., 2015). 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 (Ottosson, 2002). Design literature has also embedded rapid prototyping as a strategy to create physical prototypes more quickly and cheaply than their earlier counterparts (Campbell et al., 2007). For exploratory prototypes, Ward et al. (1995) describes 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.

2.3. Constraints on prototyping

Around each set of design problems, there are constraints that affect the strategies designers decide to use. Onarheim (2012) 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." 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. (2012) also mentions cost and "availability of machine or human resources" as design constraints that typically affect artistic design domains. Given the unique challenges faced by the industry partners in this setting, this literature will be used to further examine prototyping constraints.

2.4. Impact on design outcomes

Design researchers have examined how different prototyping strategies correlate with design outcomes. Verganti (1997) examined the role of prototypes in stimulating design team discussion. 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 (Horton and Radcliffe, 1995). Elverum and Welo (2015) found that prototypes were an effective means of persuasion between stakeholders in complex system design teams. Other researchers have examined how prototypes can influence innovation or novelty (Tidd and Bodley, 2002). For example, one study has shown how physical models can help reduce design fixation faced by designers (Viswanathan et al., 2014). Another study has demonstrated the use of prototypes for user interaction among innovative design teams (Leifer, 2000). Campbell et al. (2007) 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. The prototyping strategy used to reach the designer's goal can impact the time and cost spent on building prototypes (Hannah et al., 2012). Another study has shown that taking a concurrent engineering approach helps speed up the product life cycle compared to a sequential approach (Ottosson, 2002). This study builds upon this work to further examine the impact of certain prototyping strategies in different settings.

2.5. Design for base of the pyramid

Research into resource-constrained settings has demonstrated that new design methods are necessary (Prahalad and Hart, 2002; London et al., 2010). Prahalad (2009) developed the Base of the Pyramid (BoP) concept and identified emerging markets as a future growth for new product development. Donaldson (2006) examined the impact of unique operating conditions and differences in the user populations on the product development strategies used in less industrialized economies. Previous work by the second author similarly found that micro-entrepreneurs in these contexts might require specific strategies to meet their needs (Austin-Breneman and Yang, 2013). One group of researchers explored a method of applying existing optimization techniques to the unique domain of design for the developing world (Wasley et al., 2017). Viswanathan and Sridharan (2012) used university-based projects in India to highlight how these types of problems change the concept development and prototyping process. 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. (2011) proposed prototyping with slow refinement and extensive user testing to encourage adaptability to local environments. Schlecht and Yang (2014) suggested more novel ideas were found when resources, such as access to machine tools and raw materials, were constrained early in the design process. Donaldson (2006) found prototyping iterations were focused on imitating existing products and were limited to "achieving passable functionality." This work is used to inform the study of prototyping methods and impacts on design outcomes in resource-constrained settings.

2.6. 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.

3. Methodology

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

3.1. 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 1.

3.2. 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.

Table 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	Cook Stoves

3.3. 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 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 authors' initial research case and interview questions. Then

Table 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? • How do you define prototyping? • 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?

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.

4. 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 cook stove, a briquette-making machine, and a handcart. Fig. 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, 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.

4.1. 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 3 and a detailed summary of the constraints sorted by SME location and participant nationality is shown in Table 4.

4.1.1. 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.

Table 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

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

(a) Waste transfer cart. (*Kuklov, Vadim*) (b) Anaerobic baffled reactor.

Fig. 1. Examples of studied prototypes (Kuklov, Vadim).

Table 4
Key constraints by nationality and location.

	RWANDA		KENYA	
U.S. EXPAT	*Constraints*	*Participant Count (out of 4)*	*Constraints*	*Participant Count (out of 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 (out of 2)*	*Constraints*	*Participant Count (out of 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

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.

4.1.2. 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.

4.1.3. 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 anytime 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.

4.1.4. 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.

4.1.5. 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 R&D 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 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 cook stoves, 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 were 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.

4.1.6. 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.

4.2. 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.

4.3. 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?"

4.4. 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.

5. 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 (Houde and Hill, 1997) using a "works-like" model (Koo et al., 2014) and for the key purpose of learning (Ulrich and Eppinger, 2012). 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 (Brown and Wyatt, 2010). Simplicity has been defined as lower part count, which leads to the outcomes of having less to design, fabricate, test, assemble, and maintain (Yang, 2005). 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 R&D 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.

6. 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 SMEs 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.

6.1. 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 to 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.

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