Development Engineering 3 (2018) 117–124

Contents lists available at ScienceDirect

Development Engineering

journal homepage: www.elsevier.com/locate/deveng

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

ARTICLE INFO

Keywords:
Design for development
Prototypes
Developing countries
Prototyping methods
Design for manufacture
Engineering for global development
Design for the developing world

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).

https://doi.org/10.1016/j.deveng.2018.05.002
Received 12 September 2017; Received in revised form 31 January 2018; Accepted 3 May 2018
Available online 5 May 2018

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