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Impact of prototyping resource environments and timing of awareness of constraints on idea generation in product design

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ABSTRACT

Research and development laboratories in universities and firms around the world try to maximize innovation with a limited set of resources. However, questions remain about the influence of resource constraints on idea generation in early-stage product design. Multiple embedded case studies were conducted with engineering students and faculty at two university campuses in Mexico. Students developed sketches for products that would satisfy an open-ended design problem in a constrained-resource setting, where the variables were the timing of when information about these constraints was revealed, and the regular prototyping environment of the student. The evidence suggests that the timing of awareness of constraints can have an impact on design outcomes, but that this effect varies depending on the designer's regular prototyping resource environment.

1. Introduction

There is increasing global pressure for engineers around the world to design high-quality, innovative solutions to societal problems, while actively considering costs and available resources. This tension is especially strong in emerging and developing countries, which seek to maximize the impact of their investments as they push to develop local engineering design capacity.

This invites the question, is design really universal? Are design methods appropriate for all settings? Prototyping resource environments vary around the world, so optimizing design strategies based on research in high-resource contexts, and "exporting" those strategies may not necessarily be the only (or the optimal) option. This paper will explore both the notion of a prototyping resource environment and its role in idea generation, as well as potential strategies for creating better designs within a constrained environment.

2. Previous research

2.1. Prototyping resource environments

A firm's "culture of prototyping," can be better understood by examining prototypes and specifications, prototyping media, and the prototyping cycle (Schrage, 2000). This culture can affect how people approach situations in their current organization, can provide insight about their default strategies and how engineers will approach future projects (Henderson and Clark, 1990). A *prototyping resource environment* is a term proposed in this study to describe a subset of the culture of prototyping. The environment can be described by a collection of factors including access to physical resources, such as materials and tools, and the cultural emphasis on resourcefulness, which can be influenced by economics and sustainability concerns. It describes the resource context that engineers find themselves in when designing products.

Case studies of practice suggest that designers should rapidly make multiple prototypes in order to quickly test design concepts and make modifications (Kelley and Littman, 2001) and that prototypes are valuable learning tools (Yang, 2005). However, there is concern by some educators that by focusing on rapid assembly, with little regard to the life cycle of the materials, this approach inadvertently teaches students that waste is acceptable in the design process (Gerber et al., 2010). Analyzing prototyping resource environments and supply chains (and their impact on product design) could yield insights about how to improve engineering education and design outcomes in any setting where cost constraints or minimizing waste are a large concern.

2.2. Supply chains and design

Supply chains vary across the world, and for a technology to be appropriate to the local context it also needs to work within the existing environment (Smith, 2008). If devices should be designed taking into account the local context, why not the design process?

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Three-dimensional (3D) concurrent engineering is based on the principle that decisions of product, manufacturing, and supply chain development must be made in integrated product development teams. For a student or inventor designing and manufacturing their own prototype, this would entail incorporating all three perspectives earlier on in the design process. Adopting 3D concurrent engineering practices can be crucial for success, and firms that do not add supply chains to their concurrent product and process decisions often encounter problems and unforeseen costs late in product development (Fine, 1998).

Other case studies have also supported the notion that aligning supply chain capabilities and integrating perspectives early on in the design process can lead to more successful designs. A firm could develop a design, but if users are not ready for it or if suppliers cannot create the necessary components, the product will most likely not be successful in the market (Afuah and Bahram, 1995). Understanding the influence a supply chain can have on the success of product design is especially important in resource-constrained settings where designers may not have the financial cushion to make mistakes.

2.3. Resource constraints and idea generation

With the economic and environmental concerns of industry, design research has turned to look experimentally at the effect of prototyping materials and tools on the design process of individuals (Culverhouse, 1995; Noguchi, 1999). Another study on the effect of prototyping constraints on design outcomes used the amount of materials, time, and task constraints as variables (Savage et al., 1998). One component of the explanation by Savage et al. for the reduction of the range of design ideas with greater cost constraints was that perhaps the designer's "frame of reference" changed when constraints were introduced, reducing the solution space that the participants considered (Akin and Akin, 1996).

However, the literature has also suggested the opposite; that greater constraints could lead to more novel results. When faced with a design task, designers tend to prefer to retrieve a "previously constructed solution," following the "path-of-least-resistance" (Ward et al., 1999). If constraints are sufficient, they may be forced to leave the path of least resistance and construct a new plan (Moreau and Dahl, 2005). Therefore the impact of constraints may not be an absolute effect, but dependent on the flexibility of the designer and how they define the solution space.

The literature on entrepreneurship also explores why some people are somehow able to "make something from nothing." In adverse environments, there may be many available resources, but *key* resources are constrained, which gives rise to unmet needs and provides an opportunity for inventive people to reroute resources in order to meet the need (Chakravorti, 2010). Perception of resource adequacy is not always solely based on the absolute level of resources, but can also depend on the designer's frame of reference (Gibbert et al., 2007). So how do we foster more "entrepreneurial" designers who can thrive in constrained resource settings?

Constraints are inevitable in the design process, and there are many ideas on how to deal with them. Most, however, are quantitative methods that require some knowledge of the "technology function," or a quantitative equation or a qualitative objective that relates the input quantities or properties to the desired output (Ashby and Johnson, 2010; Harmer et al., 1998; Lin and Chen, 2002). These processes are therefore more useful later in the design process, when the structure of the product is already more defined, and there is a clearer set of options and a more accurate understanding of their combined impact on the outcome.

If these types of options do not work, and it is impossible to change the resource environment, the idea generation process itself can be manipulated, by controlling the timing of when information is revealed to designers (Tseng et al., 2008), or when constraints are incorporated into the design process (Liu et al., 2003). Understanding the impact of these variables, and combining it with information about the local prototyping environment and the designer's "frame of reference" could lead to low-cost strategies for increasing innovation.

2.4. What is missing

There has been substantial work on cross-cultural comparisons in design (Downey et al., 2006; Okudan et al., 2008; Razzaghi et al., 2009). However, there is a relative lack of literature on the variety of "material cultures" and their impact on prototyping and product design, especially in educational settings. Some researchers have delved into production and design in resource-constrained settings, but have focused on the industrial sector or micro-enterprises (Carvajal et al., 1990; Donaldson and Sheppard, 2004; Kabecha, 1999; Romijn, 2000). Most studies suggest that more investment is required and/or that social structures should be encouraged to create design clusters and "innovation systems" in order to lower barriers to design, although Donaldson (2006) also draws attention to the nature of supply chains in Kenya which could be obstacles to design.

3. Research

The objective of this research was to show that not only do prototyping cultures vary, but also that being trained in one may leave designers ill-prepared when transplanted to another because different mindsets and design strategies are required. Also, by focusing on the impact of resources on the design process rather than just the design outcomes, this perspective can hopefully lead to useful insights about how to construct a campus environment or curriculum to foster the development of desired problem solving skills.

The first goal of the study was to create a systems model to visually depict how prototyping resource environments relate to the design process, as well as the influence that different actors are able to exert on the system (Fig. 1). This model provided the conceptual framework for scoping and analyzing the case studies to follow.

Students are influenced by their university's institutional prototyping environment, as well as the greater economic environment. The policy instruments are the knobs that educators and policymakers can turn to change outcomes in the system, and students can manipulate design outcomes via design strategies.

In this study, this model maps to the analysis of a system (university), the higher-level context (Mexico), and subsystems (engineering students). Data gathering focused on representing the system as it is perceived by the individual designers, and then using that information to experiment with different design strategies. However, to obtain a more balanced picture of the context, interviews with students were accompanied by site visits and interviews with professors.

3.1. Research questions

The specific research questions were structured in order to gain a better understanding of the linkages and dynamics in this system, and then to isolate areas where policymakers and engineers can change the system (or work within it) in order to produce better design outcomes.