Impact of Prototyping Resource Environments on Idea Generation in Product Design

by

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ABSTRACT

Some of the world's most challenging problems will require distributed innovation capacity in order to create high-quality and sustainable solutions. However, access to prototyping resources varies and design strategies that are optimal in one context may be suboptimal in another. As the engineering practice is becoming increasingly globalized and R&D laboratories in universities and firms around the world try to maximize innovation with a limited set of resources, there is a need for greater understanding of the impact of prototyping resource environments on product design in universities. This knowledge will allow for the creation of more efficient innovation systems and help to foster more adaptable engineers.

In order to explore the relationship between available resources for prototyping and idea generation during the design process, multiple embedded case studies were conducted with engineering students and professors at two university campuses in Mexico. In a design experiment, 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 outcomes were evaluated by comparing metrics such as the quantity, novelty, appropriateness, technical feasibility and marketability of the concepts. The evidence suggests that the timing of constraints can have an impact on the design outcomes, but that this effect varies depending on the designer's regular prototyping environment. The implications of these findings for engineers, educators, and policymakers working in any setting are discussed.

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This thesis was the largest independent international research project I have undertaken and was an incredible opportunity to learn new skills and to explore engineering design from a new perspective. Without the support of all of these people, I probably would not have undertaken as ambitious a project so I am grateful for this network and all of the opportunities that it provides. I am looking forward to tackling new challenges with them in the future.

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1. Introduction

1.1 Motivation

Policymakers, managers and educators around the world are trying to foster systems of innovation in a global environment where technology and knowledge-based industries are becoming increasingly important for economic and social development. Multi-disciplinary and international solutions, taking into account a variety of perspectives are gradually becoming the new paradigm for solving problems and designing new products. Solving many of our global challenges will require distributed innovation capacity, in order to foster innovators who can design solutions that address the needs of local users and spur economic development.

The problem is that innovation resources are concentrated. In 2011, 71% of global R&D spending was spent in only 7 countries: the U.S., China, Japan, Germany, France, South Korea, and the UK (National Science Board, 2012). The majority of publications on best practices for design methods and innovation policy are also published in these countries.

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 are looking 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? This thesis asserts that as prototyping resource environments vary around the world, optimizing design strategies based on research in high-resource contexts, and "exporting" those strategies may not necessarily be the only (or the optimal) option.

1.2 Prototyping and Constrained Resources

Virtual and physical prototyping are used for generating, testing, and communicating new product ideas during the early-design stage (Brereton & McGarry, 2000; Houde & Hill, 1997; Lande & Leifer, 2009; Viswanathan & Linsey, 2009; Yang, 2005). Engineers often develop prototypes in order to answer questions about the function, form, or interaction with the product, and prototypes can incorporate a wide range of detail relative to the final product. They can be models of a specific aspect of the product using un-finalized materials, or a complete replica of the entire product.

Some designers also make "throwaway" prototypes out of paper, cardboard, foam, or other materials with the knowledge that this prototype will be later discarded and not incorporated into the final prototype. The decrease in cost and increase in availability of various prototyping technologies have expanded the possible choices. Prototypes can be made in a state-of-the-art rapid prototyping laboratory or built using a couple of hand tools. Improvements in the user interfaces and computing capability of computer-aided design software have also influenced the workflow of designers. With the increased number of options for prototyping, there is considerable academic and professional debate over which prototyping strategy (or mix of strategies) produces the best design outcomes.

Traditional design approaches tend to start with idea generation and analysis, moving into material acquisition and prototype building later on. This process is unproblematic if engineers can find the parts they need or close substitutes, but there are places (and design problems) in the world where this approach is not always appropriate because options are limited.

There are competing philosophies on which types of prototyping environments lead to the best design outcomes. The controversy is based not necessarily on the perceived benefit of prototypes, but on the financial, time, and material costs incurred in relation to the value gained from constructing a prototype. As some industry studies have linked up to 75% of total product costs to design decisions, focusing on early-stage design and prototyping is important for investigating strategies for dealing with the tradeoffs of design and cost (Soderberg, 1989).

Some designers encourage making a lot of physical prototypes throughout the design process, in order to answer questions and spot problems early on (Viswanathan & Linsey, 2011). Other designers are concerned about the financial and environmental costs of prototyping. The prototyping techniques and strategies students learn in school influence how they design in the workplace, and engineering educators are especially concerned about what they are teaching new engineers. Some academic studies have suggested a positive link between prototype building and student learning. However, others have expressed concern that encouraging the use of foam core and multiple prototypes in design classes (even if the materials are relatively cheap compared to full-scale manufacturing) sends the unintended message that waste is acceptable. Engineers and designers all over the globe are increasingly conscientious of the need to generate better designs with less financial and physical waste, and educators and managers in lower-income settings are especially concerned about maximizing the value of their investment in equipment and materials.

Besides improving design outcomes in constrained-resource settings, this thesis was also inspired by anecdotal evidence that has suggested that students trained in higher-resource settings can sometimes be less adaptable than their counterparts who have had to work with less resources and therefore needed to be more flexible in their design process. How can we foster more adaptable designers who are prepared for any type of context? Can we learn something about product design from engineers who are working in relatively more constrained settings?

1.3 Thesis

This research project was formulated around the notion that prototyping resource environments are a linkage between innovation policy and early-stage design outcomes. The discussion in this thesis is based around the statement below,

The major players in an innovation ecosystem (government, universities, and firms), set policies which influence the prototyping environment, impacting engineers and designers who apply design strategies to produce design outcomes.

This thesis will attempt to provide a conceptual framework for understanding these relationships and their impact on the design process, and support for this model through results from multi-method, embedded case studies following the design process of a small selection of engineering students in two Mexican universities. With a systems model, it will be easier for policymakers and designers to better understand the interactions and feedback loops within their own systems, and it will also provide guidance on how they can change the system and its outputs.

1.4 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.

How does the prototyping resource environment influence the design process and idea generation?

Assuming the designer is working in a constrained environment, does the timing of information about prototyping resource constraints influence design outcomes?

How can policymakers and system designers influence the prototyping resource environment and the design process?

1.5 Contributions

This thesis proposes a systems perspective for analyzing the impact of policy decisions on the prototyping environment, and therefore on designers and engineers. It also explores the potential impact of the timing of constraints and the individual's frame of reference given their usual prototyping environment, both of which have received less attention in the debate on the influence of constraints in the design process. This type of multi-method case study, incorporating a broad view of the designer's prototyping environment with a study on an individual's design outcomes, has not been done before in a university setting, especially with this particular population of participants.

1.6 Thesis Outline

Chapter 1 provides a brief overview of the motivation and general approach of the study.

Chapter 2 is an overview of the relevant literature and prior work in this area, starting with a broader perspective of the role of innovation policy and design in development, moving into a discussion of economics and supply chains in firms, and finally providing an overview of previous work on the influence of these factors on an individual's design decisions.

Chapter 3 describes the conceptual models that were used to frame the data collection and analysis phases.

Chapter 4 provides a description of the methodology used to collect and analyze the data during these multi-method case studies.

Chapter 5 presents some of the quantitative and qualitative results of the study as well as a discussion about what relevant theories could explain these results.

Chapter 6 discusses the potential implications for product designers, and suggests design strategies and curriculum modifications. It also provides some guidance to policymakers and system designers on how they can incorporate this framework into the analysis of their own systems, and recommends some strategies for changing prototyping resource environments.

Chapter 7 summaries the findings of this thesis and provides suggestions for future work.

Chapters 8 and 9 provide references and copies of the experimental materials respectively for those interested in learning more about these topics.

2. Background and Relevant Theory

2.1 Intro to the chapter

The following sections will lay the theoretical foundation that supports and justifies this study. Beginning broadly with a discussion of the role of design and innovation in development, it will progress to looking at the relationship between resources, prototyping, and design at a firm level, and finally, to examining the impacts on individual designers (Figure 1).

Figure 1. The chapter will progress from a macro policy view to the relevant literature on prototyping and resource constraints in firms, and finally to design research on individual designers.

This study is based on a systems perspective of product design, with a particular focus on how the materials and tools in the system impact designers and their design processes and outcomes. The objective of this chapter is to set up the motivation for the design of the study by first exploring the literature surrounding two approaches for solving problems: dreaming big, increasing investment, and lowering barriers vs. using constraints to incite innovation (Figure 2). These themes will be revisited throughout the rest of the thesis.

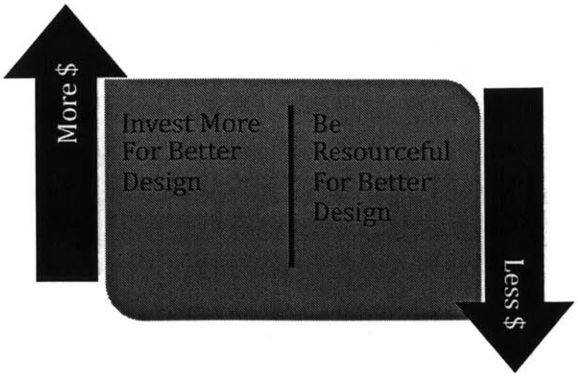


Figure 2. The debate concerning the impact of resources on product design

The literature tends to follow a "north-south" divide concerning discussions of product design and available resources. However, these themes are universal, even within a country, regardless of the level of industrialization and there are also discussions of these themes in the literature comparing product design in start-ups vs. large established corporations.

The term "development" in this thesis is used in the sense of growth or progress, and is meant to refer to economic and product development regardless of the starting point, and therefore these ideas are applicable to any type of setting. However, the discussion was consciously focused on the concerns of designers in lower-resource settings (as compared to the average lab in the United States), as they are traditionally underrepresented in literature on design methods. Discussions about resource constraints and innovation often mention markets at the "Bottom of the Pyramid" or people making less than $2 a day (Prahalad, 2005). Designing for and in these settings often involves extreme resource constraints. The term "resource-constrained" used in this thesis is meant to incorporate the bottom of the pyramid but also other settings in transitional or industrialized markets where designers may find themselves more constrained than their competitors, or more constrained compared to previous design environments.

This particular thesis and the selection of the cases was motivated by the author's personal experience designing in Mexico. However, the lessons learned could be applied to a variety of other settings. As a middle-income country, with a large range of income and development throughout the country, there are variable levels of resources and types of product development and R&D projects. The following discussions will focus on the political and product development theories that are most relevant to the Mexican context and similar settings.

2.2 Technology, Design, and Development Policy

Technology has generally been viewed as an important vehicle in the economic and social development of a country, especially over the past century (Gargione, 2006; Schumpeter, 1934; Solleiro & Castañón, 2005). The general debates on innovation policy in less-industrialized nations have focused on identifying where to make larger investments, in order to "catch up" to richer countries. This sentiment is so prevalent that it is difficult to find a policy recommendation that does not include "higher R&D investment." However, in countries and firms with limited budgets and competing demands for investment, this recommendation becomes more difficult to implement. There are also system dynamics that can impact the effectiveness of funding, regardless of how much money is pumped into the system, such as national strategy, alignment of capabilities, and the prototyping resource environment. Therefore understanding their innovation system and identifying the best places to focus their investments is especially important for resource-constrained settings.

2.2.1 The "Design Frontier"

In order to determine how to improve performance, firms and countries are often looking for a way to benchmark their performance against others. With such diversity within countries, characterizing countries or firms as more "advanced," "developed," or "industrialized" has certain disadvantages from a product design perspective because it provides an ambiguous and overly simplified picture of the design context in that country. This classification also does not take into account the distribution of resources within a country or strategies for differentiation.

A more productive and universally applicable method may be to instead characterize firms, industries, or countries in terms of technology followers and leaders. The leaders set some bar that followers aim to reach and surpass. Innovation is expensive and risky, so followers are able to innovate through a combination of trade and local absorptive capacity (Fu, Pietrobelli, & Soete, 2011). However, development does not need to follow a linear path, and disruptive technologies can emerge from the most unlikely sources. Therefore a boundary analogy may be more appropriate for thinking about development because it allows firms and countries to decide how they will add value by either pushing towards the boundaries or by defining them.

For technology-follower countries, pushing the design frontier may be a better strategy to pursue in order to make a global impact with less investment and risk. Forbes & Wield highlight that technology-follower countries cannot compete with leaders in terms of R&D spending (Forbes & Wield, 2002). However, they also argue that because these countries are followers, their structure of R&D should be different and therefore higher budgets are not necessary. They assert that design, an application of existing technologies to market needs, is where technology followers should focus their capacity efforts, because it can be a vehicle for addressing local market problems at a lower cost than pushing the technology frontier would require. Design can be an important vehicle for economic growth and technological learning, but the prototyping process often requires significant investment in equipment and materials in its own right.

2.2.2 Improving Technology and Design Capacity

Most of the recommendations for innovation policies have focused on attracting foreign direct investment, improving education, increasing funding for R&D and improving linkages and information flows via innovation systems and industrial clusters (Aubert, 2005; Rosen, 2011). Value chains have also been a focus of development writers (Pietrobelli & Rabellotti, 2010). Policies aimed at improving supplier linkages with TNC, and MNCs. Costa Rica's "Costa Rica Provee" program was designed to encourage local sourcing by TNCs and Mexico's TechBA program was aimed at integrating high-tech SMEs into global value chains (Costa Rica Provee; Tech BA, 2012). Especially in global supply chains marked by foreign direct investment, multi-national corporations, and tightly vertically integrated supply chains, the value chain can be a source of product design improvements, along with process and marketing improvements. These policies look at production supply chains but there are also prototyping supply chains that affect designers in both firms and universities. Some governments, such as South Africa, have recognized this and are also increasing investment in prototyping and manufacturing technologies (Campbell & de Beer, 2005).

2.3 Prototyping Resource Environments and Firms and Universities

Production and innovation in firms is a great source of potential models for product design and prototyping in universities and low-resource settings because of the multivariable characteristics that need to be considered, from technical performance and customer needs to economics and supply chains. Understanding this dynamic can provide a framework for exploring the impact of supply chains and resource environments on product design at a university and firm level.

2.3.1 Resource Environments

Multiple studies have been conducted on the relationships or correlations between resource levels and firm performance. The notion of a resource environment is prominent in business literature, and the role of adversity and limited resources has been explored at length in the field of entrepreneurship.

In adverse environments, there may be many available resources, but *key* resources are constrained, which gives rise to unmet needs and can cause other resources to be redundant, which provides an opportunity for inventive people to reroute the resources to meet the need (Chakravorti, 2010). Chakravorti found that entrepreneurs facing adversity "tune into the particular opportunities that characterize challenging times" as compared to entrepreneurs in less-constrained settings.

While traditional management theories suggest that performance is linked to material resources, others argue that resource adequacy depends on the designer's point of view, and that "resource-driven thinking" (the notion that the competitive advantage of firms lies in their distinct "bundle" of resources) could be impeding sources of innovation (Gibbert, Hoegl, & Välikangas, 2007). Constraints can also inspire problem solving and design, depending on the challenge.

2.3.2 International Cultures of Prototyping

Investigating human interaction with artifacts has long been a method for understanding the values, culture, and opportunities for change within an organization or society. "Material culture" is a term that emerged in the social sciences, as a way to discuss culture through the lens of the relationships between people and artifacts. Just as archeologists study the artifacts of past societies to better understand them, observing physical objects and how people interact with them can reveal information about the culture's values.

There have been a number of case studies aimed at describing the material culture of firms. Quirke investigated the links between the material culture of British pharmaceutical laboratories and innovation in the drug industry, providing a chronological description of the lab construction and layout, technology purchases and mapping these characteristics to drug inventions (Quirke, 2009). Carvajal, et al. surveyed characteristics of microenterprises around Mexico City, including their use of materials and production processes (Carvajal, Fiedler, & Gonzalez, 1990). Vinck conducted a case study looking at how engineers interact via "intermediary objects" such as drawings, documents, and prototypes and determined that the creation of these objects can reveal insights about how negotiation and communication is carried out in the organization (Vinck, 2011).

Schrage is one of best-known advocates for investigating "cultures of prototyping," which can reveal insights about the management style, values, and potential success of the firm's products (Schrage, 2000). He asserts that the culture of prototyping in an organization can be better understood by examining prototypes and specifications, prototyping media, and the prototyping cycle. This culture can affect how people approach situations in their current organization and can provide insight about their default strategies. When faced with a new problem, engineers often focus on applying the information that they have gathered in previous projects. This includes applying problem solving strategies that have been successful in the past (Henderson & Clark, 1990). Therefore reinforcement from their existing prototyping culture can influence how designers will approach future projects.

There has been substantial work on cross-cultural comparisons, a body of which focuses on the impact of national culture on the working styles, design ideas, and worldview of engineers and designers. Researchers have looked at how national values are embodied in design sketches and physical artifacts (Okudan, Thevenot, Zang, & Schuurman, 2008; Razzaghi, Ramirez Jr., & Zehner, 2009), or how the view of the role of engineers differs internationally, in order to educate students and foster "globally competent" engineers who are equipped to work with multiple cultures (Downey, et al., 2006).

However, there is a relative lack of literature on the international variety of "material cultures" especially as it relates to prototyping in university settings. Prototyping is a major component of engineering and has been cited by researchers and students as a critical format for learning. While there are some assertions that the globalization of technology is causing the relationships between people and machines to converge, in many areas of the world, there are a variety of "prototyping environments." Even two settings with identical prototyping labs could have different processes for prototyping due to material availability and culture. Beyond the materials and tools for prototype construction, economics also plays a large role in the culture of prototyping, especially as financial resources become more constrained or the relative cost of prototyping increases.

2.3.3 Economics of Prototyping

Engineers are constantly making trade-offs while designing. Firms will also make decisions not just on technical requirements, but available human, physical, and financial resources, the market, and general socio-political-economic contexts. An engineer developing a prototype is essentially carrying out multiple roles at once and has to balance out the requirements of each. Wells describes this dichotomy as an internal debate between the "economic man and the engineering man," in his 1972 report explaining the choice of manufacturing technologies by managers in Indonesia (Wells, 1972). He asserts that the decision maker is considering the tradeoff between two objective functions, that of the "engineering man" to pursue more sophisticated, automated technology, and that of the "economic man" to minimize costs.

This framework is applicable to engineering students or designers who are developing a prototype, either by themselves or on a small team. On one side, they are an engineer and designer, deciding the physical form that the product should take to solve the problem in question. While prototypes are not necessarily, and often not meant to be, accurate representations of the entire product, constructed in the same manner that final production would require, all useful prototypes are meant to demonstrate an idea or test a hypothesis, so an engineering eye must be used to decide which options to incorporate and how to organize the system. The engineer/designer incorporates market information in the design of the form and function of the product, but this viewpoint is more focused on how to design the product in order to best address the functional requirements. Engineers and designers are often drawn towards high-tech, interesting, and elegant designs and tend to always want to accomplish more and perfect their designs.

At the same time, an engineer developing a prototype must also think about manufacturing. They have to choose materials that will best illustrate the component or test a mechanism. If they build the prototype themselves or send it out to be manufactured, they have to consider machining capabilities and tolerances in order to make trade-offs between detail and time. They need to think about assembly and disassembly, and perhaps re-use of components or modules, to permit experimentation and changing their design.

An engineer making a prototype is also acting as a manager. They need to decide how many and what type of prototypes are necessary to convey the idea, obtain feedback, and run tests, while saving time and money. They often need to coordinate design and fabrication of the prototype to work with time constraints of ordering and receiving parts from suppliers, using the prototyping equipment and dealing with machine downtimes. They also need to factor in time for required re-works, and deal with scrap material. The majority of projects are constrained by a budget, either from grants, classes, or the engineer's own pocket, so they need to make economic trade-offs as well.

Wells discusses the fact that the context of the firm will determine which of the personalities will win out over the other. For example, in a price-competitive market, he found that the "economic man" tended to override the "engineering man," while the "engineering man" was able to win out in firms that had more of a monopolistic position. Relating this observation to prototyping, budget and resource restrictions could force the designer to make decisions based more on economic factors, while a larger budget and more options allow the "engineering man" to take over. Both viewpoints are extremely important, especially as engineers are required to innovate with increasingly constrained resources.

To address the challenge of dealing with engineering and economic tradeoffs, Thomke proposed a framework for deciding when to use different modeling tools depending on the experimental cycle and tool efficiency (eliminated errors/cost) (Thomke, 1998). However, while this heuristic is useful in deciding which technology is more cost effective when running experiments after the concept is generated, it does not address the influence of economic concerns on the idea generation phase.

2.3.4 Environmental Impact of Prototyping

Beyond the financial costs, there is also an environmental cost of the energy and materials required during the product development. Life cycle analysis is often applied to supply chains, but there has been very little focus on prototyping. Foam core, a material often used in architectural and industrial design, has a very hazardous life cycle. Petrina described the political ecology associated with the typical design method, arguing that in developing a product design *resource stream*, we inherently embedded our culture's values on consumption and production (Petrina, 2000). There is a growing feeling that design needs to shift towards sustainable design outcomes, and also a sustainable design process.

MIT and some other engineering schools in the U.S. encourage students to rapidly make multiple prototypes in order to quickly test design concepts and make modifications. 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, Mckenna, Hirsch, & Yarnoff, 2010). In order to consider material use and waste during the design process, zooming out and examining prototyping supply chains could be a source of insights for improving design labs and curriculum.

2.3.5 3D Concurrent Engineering

Creating a physical prototype requires many similar decisions and steps as developing, manufacturing, and launching a product, albeit at a smaller scale. Some researchers have suggested that many of the theories of production management could be applied to design, such as waste, queuing theory, and improvement (Ballard & Koskela, 2009). Supply chains and inputs to the prototyping process can also be modeled, which allows designers and project managers to keep track not only of allocations of financial and human resources but to better understand the impact of physical inputs, and capital goods on design outcomes. This is especially salient in settings where inputs are a large factor in design decisions.

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. Technology must be "transparent" (the workings of the technology must be understandable to the community), innovators and producers need sufficient access to supply chains (to produce and market the technology), and they need access to capital to finance production and equipment

(Smith, 2008). If devices should be designed taking into account the local context, why not the design process?

In the design of supply chains, one key concept is inventory. Many design firms and educators advocate having a lot of materials available for designers to play with. However, while this strategy decreases lead times and transportation costs, it is accompanied by a larger inventory, which translates to higher storage costs and upfront capital. Given the variety of projects and material inputs, and the smaller volume sizes required for prototypes (as compared to a manufacturing supply chain), maintaining the large inventory of parts could be more expensive. Also, stocking parts onsite requires greater storage capacity, which means space and capital is taken up for materials that are not currently adding value.

Many design projects in educational settings and design experiments are designed with a constrained kit of parts for students to use in order to create their prototypes. While the constraints are often meant to even the playing field for fair comparison of designs, they also help to reduce uncertainty and procurement costs because components can be bought in bulk at a discount before the design course begins. This also helps to reduce lead times because the materials are available to students from day one. Completely unused materials are restocked in the following years' kits, while scraps are often discarded or recycled.

This type of prototyping supply chain would be characterized as a centralized system, where a central authority makes decisions on materials and suppliers, which can help to achieve global optimization. Projects where each individual student or team of students are in charge of procuring materials allow them to decide on the most effective strategy for obtaining supplies would be a decentralized system, which helps encourage local optimization.

While supply chains play a role in any product development setting, whether for a prototype or the deployment of a new high-tech product, there is relatively little explicit discussion on how to incorporate supply chains into the early-stage design phase, when compared to concurrent engineering or user-centered design. Three-dimensional (3D) concurrent engineering is based on the principal 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.

This is not just a concern for less-industrialized or resource-constrained settings. Fine suggested that strategic decisions about supply chain and product architecture are especially important in clock-speed industries, where customer requirements change rapidly (Fine, 1998). He actively supports 3D concurrent engineering, maintaining that firms that do not add supply chains to their concurrent product and process decisions often face problems later in the process, late in product development or at the launch of manufacturing, logistics, quality control, and production costs. He provides an example from Intel, where they had historically used a mounting system that required nine machined metal pins. They re-designed the product after the supply chain team found out that the number of required machine tools for making those parts did not exist anywhere in the world.

Other case studies have supported the notion that aligning capabilities and integrating perspectives early on in the design process can lead to more successful designs. Afuah and Bahram presented a model of a hypercube of innovation, asserting that different players along the value stream, such as suppliers and customers, may characterize the change differently, as either radical or incremental innovation, and therefore project managers should take this into account in order to ensure the success of their designs (Afuah & Bahram, 1995). 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.

While students are often taught about design for users, very little curriculum covers design for suppliers, even though many case studies cite its advantages. The traditional design process often encourages conceptual design for users and technical performance, with design for suppliers coming in either during concept selection or at the end of the process. This approach may be fine in settings with multiple supplier options, but in constrained environments, this can result in a lot of unusable designs and design re-work. As multiple researchers have stated, understanding the needs and capabilities of everyone on the supply chain is important for a project to be successfully implemented.

There are different design techniques for procuring parts from suppliers. One technique is to develop a bill of materials and source all of the parts, manufacturing some in-house. Another technique, utilized by Toyota with their suppliers is "black box supplier design" in which vendors are told what the part needs to do, not how it should do it (Clark & Fujimoto, 1991). This requires a system-level design and clear definition of the interfaces. Co-collaboration between users, innovators, and suppliers can also be an option and can result in spillovers of knowledge and increasing linkages beyond formal institutions in knowledge economies.

Fine et al. refer to the importance of coordinating the design of the product and supply chain architecture, as either both modular or both integral, in order to maximize performance (Fine, Golany, & Naseraldinb, 2005). The choice of product system architecture often depends on the desired characteristics of a product. A product with a modular architecture incorporates a collection of physical components, and each chunk completes a certain set of functions in their entirety. The interactions between the chunks are clearly defined (Ulrich & Eppinger, 2008). With integral product architecture, the functional components are implemented across multiple physical components and the interactions between the elements are ill defined. The choice of product architecture determines how the product can be changed, product variety, component standardization, product performance, manufacturability, and product development management. The choice of product architecture will affect manufacturing needs and the efficiency of supply chain options. With this in mind, could designing "backwards" help create better products within existing upstream supply chains and manufacturing capabilities?

Besides considering product architecture, designers also have design choices about what components to design, select, make, or buy. Ulrich and Ellison define the *design-select* decision as a continuum of options, from designing their own components to selecting components from supplier catalogs (Ulrich & Ellison, 1999). This is differentiated from the *make-buy* decision, which concerns the manufacturing stage and the choice of either making the component themselves whether or not they designed it, and sending it to an outside manufacturer to be fabricated. Singhal and Singhal describe six options along the design-select continuum (Singhal & Singhal, 2002). Benefits of selecting existing components include: minimizing investment, economies of scale, and organizational focus. Designers may choose to design their own component when adequate options are inexistent or unavailable, or in order to optimize product performance, minimize size, mass, and variable cost. Ulrich and Ellison suggest focusing design effort on components that map to multiple customer requirements, and to select components that are linked to few customer requirements. However, these types of decisions are often made after the idea generation stage. What is the impact on idea generation if options are constrained?

2.4 Impact of Resource Constraints on Individual Designers

Diving deeper into the impact of prototyping resources on design, they can also impact the decisions made by individual designers. Many of the reports on engineering design in resource-constrained settings have been case studies of particular technologies or companies (Daniels, 2011; Ray & Ray, 2010). These tend to discuss the design outcomes, produced by entrepreneurial designers that contradicted expectations of what could possibly be created in that environment. Many of these stories either glorify the resourcefulness of these companies and designers, decreasing the accessibility to the majority of designers, or, they downplay the outcomes, as perhaps a less desirable process, if the resourceful decisions were not consciously made after a careful engineering weighing of the objectives and constraints.

The proposed strategies for design in resource-constrained settings often focus on design *for* rather than *in* a constrained setting, stressing the need for understanding the user and use context, creating an organization that values innovation and divergent thinking, and improving business models and public policies (Chandra & Neelankavil, 2008; Krishnam, 2010; Simanis & Hart, 2009).

The focus of the discussion is mainly focused on the outputs or organizational factors in the design process. There is a much smaller body of literature that attempts to describe the impact that access to physical resources has on the product design process and outcomes in constrained-resource settings. There is room in the literature for more in-depth exploration of what causes the design decisions of engineers working in these resource-limited settings, and for clear design strategies and suggestions on how to produce better outcomes when the context cannot be changed.

2.4.1 Creating Something from "Nothing"

Traditional theories on the impact of resource environments on firms have considered resources to be objective, fixed and allocated. Some argue that each firm has its own relationship with its resource environment (Penrose, 1959). This could be extended to individual students. With this perspective, "creating something from nothing" becomes less mysterious and more attainable. Combining existing components to create novel and appropriate products could be a useful design tool to supplement other idea generation techniques.

Three major components of literature on bricolage include resources at hand, recombination of resources for new purposes, and making do (Baker & Nelson, 2005). The French term is similar in use to "hacking" in the U.S. or "jugaad" in India (Krishnam, 2010). Some Mexicans refer to products that require resourcefulness as "mexicanado." Engineers and educators in Mexico have discussed this level of creativity in both positive and negative ways, praising the creativity required to find a solution with limited resources, but lamenting the lack of structure and analysis in the development and testing of these solutions. The question is, what is the best way to train analytical thinkers, engineers, in bricolage so that they are able to combine the best of both worlds?

While material constraints can inspire unorthodox use, they could also cause design fixation, or functional fixedness as it is referred to in the psychology literature. Adaptations of Duncker's experiments have shown that how the material components are shown to participants, as in whether the material is shown in its primary usage state, influences their time-to-solution (Adamson, 1952). There is also evidence to suggest that this behavior is universal and also prevalent in areas with fewer resources (German & Barrett, 2005). However, German and Barrett did not directly compare their results to a higher-resource setting, so it is not clear if there is an influence of setting on speed.

2.4.2 Resource Constraints and Product Design

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. Studies have looked at the impact of material use on the design of products (Noguchi, 1999). Some researchers have argued that artificially constraining designers and their design tools, could help control "unwanted innovation" that is more costly or unnecessary for the firm's particular goals (Culverhouse, 1995). The literature suggests that the type of constraint could have an impact on whether the effects are positive or negative.

Other studies on the effect of prototyping constraints on design outcomes have used the amount of materials, time, and the task as variables (Savage, Miles, Moore, & Miles, 1998). Their study comprised simple desktop design tasks for constructing objects out of paper, and they found that the groups with certain constraints developed designs that performed better on that specific metric (i.e. used less time or less paper), but the design diversity decreased. One important component of their discussion for explaining the reduction of design ideas was that the designer's "frame of reference" changed when constraints were introduced, so instead of thinking of how they could solve a specific aspect of the problem, they approached it from a different perspective, of thinking about what they could make with the constrained materials. Previous researchers have also suggested that frames of reference play a role in design outcomes (Akin & Akin, 1996). The results of the study suggested that it was necessary to keep cost and task inherent constraints to a minimum to increase creativity. However, are there ways to get more creative results when it is not possible to relieve cost or task inherent constraints?

In their paper on constraints and creativity, Moreau and Dahl draw an analogy to a situation almost every consumer has faced: cooking dinner (Moreau & Dahl, 2005). When faced with the task of making dinner the "designer" can retrieve a "previously constructed solution," following the "path-of-least-resistance" (Ward, Smith, & Finke, 1999). If constraints are sufficient, they may be forced to leave the path of least resistance and construct a new plan.

In a design experiment, Moreau and Dahl looked at the generation of concepts for toys, where one group selected the shapes that would inspire their concepts, while the other group was given shapes by the researchers. They found that the participants who had the shapes selected for them were more likely to produce creative results because they could not immediately implement their initial ideas. They also varied whether participants were required to use as many of the shapes as they wished or all of the shapes in their designs and found that the participants who needed to use all of the shapes that were selected by someone else ended up creating the most creative designs. However they also took longer to generate ideas because presumably more cognitive effort is required the further the designer is required to deviate from the path of least resistance.

2.4.3 Design Strategies for Working With Constraints

There are many ideas on how to deal with constraints during the design process. Most however, are quantitative methods, from algorithms for determining the optimal design under constraints to using material selection charts to narrow down choices given performance objectives, such as functional, structural, and emotional requirements (Ashby & Johnson, 2010; Harmer, Weaver, & Wallace, 1998; Lin & Chen, 2002). Most of these tools 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. 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 more clear set of options and their combined input on the outcome.

Other methods such as Design for Assembly and Design for Manufacturing have certain go-to design strategies such as reducing part count. Standardizing components, simplification, delayed differentiation, and using supportive knowledge management tools can also help resource-constrained small and medium size enterprises (Singh, Matthews, Mullineux, & Medland, 2009). However, those strategies were developed with a specific factory environment in mind, which means while they do provide some direction, they are not a universal checklist, as production capability varies around the world.

The dominant strategy that design researchers advocate for is divergent to convergent idea generation. A divergent design stage encourages relaxing constraints on the designers, with the goal of helping them to explore a wider solution set, while a convergent stage focuses on narrowing down and working within a solution set. Some suggest that a multi-level, recursive approach is "ideal" for a balanced search of the design space (Liu, Bligh, & Chakrabarti, 2003). This approach calls for increasing constraints throughout the design process. However, constraints can also inspire ideas, as in the bricolage cases, therefore some designers incorporate them earlier in the design process.

Another technique for engineering system design is to follow either a top-down or bottom-up design technique. Top-down vs. bottom-up design is a technique used in software development, but has applications to other engineering disciplines. A top-down design process is driven by requirements and specifications, and each layer is developed in more detail until reaching the components. In bottom-up design, the components are designed individually and integrated. In engineering projects, many designers switch back and forth from a top-down to bottom-up viewpoint, between looking at the objective of the project, and selecting components. The trade-off is clearer in computer science and electrical engineering, where the design blocks can be broken down into discrete chunks of code or electrical components. While there are classes of mechanical components and general system configurations that have been tested and optimized, there are still a lot of options for choosing, modifying, and connecting the components.

The design process can also be manipulated by changing the timing of when information is revealed to designers. Tseng et al. looked at the impact of the timing of similar and distant analogies on responses to an open-ended design problem (Tseng, Moss, Cagan, & Kotovsky, 2008). They observed that the information caused "priming" of functional responses, also referred to as "fixation" by other researchers. However, in their research design, they only compared the influence of introducing analogies before the design prompt was given vs. five minutes after participants were instructed to solve a design challenge. They concluded that the introduction of information makes a larger impact when there is an open-goal for solving a problem, because designers are able to recognize it as being relevant to the challenge.

Other researchers have also referred to the advantage of open goals in problem solving as "serendipitous recognition", which they define as seeing solutions to pending design problems in the surrounding environment (Wills & Kolodner, 1994). This method involves understanding the design problem and what features are important in an open enough way, in order to be able to recognize inspiration and opportunities for creative reuse of concepts and materials.

2.5 What is Missing

Stories of product designs that balanced the tradeoffs of engineering and economics have been shared in case studies of product development in resource-constrained settings but they have mostly been explained in a mysterious way, as a result of ingenuity or creativity sparked by extreme constraints, and it has tended to focus on business management rather than engineering design. There has been very little research aimed at reducing the mystery surrounding innovation in resource-constrained settings. Some researchers have delved into production and design in resource-constrained settings, but have focused on industry and micro-enterprises (Carvajal, Fiedler, & Gonzalez, 1990; Donaldson & 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 also draws attention to the nature of supply chains in Kenya which could be obstacles to design (Donaldson K. M., 2006).

The author does not contest the goal of increasing technology capacity to increase innovation. This thesis is proposing that in cases where greater investment or re-structuring is not immediately feasible, there may be design methods that will allow engineers to create better products without requiring more resources. Other studies have suggested the positive impact on design outcomes of solely providing divergent thinking training to a variety of populations including engineering students and managers, as well as artisans and farmers in low-resource settings (Girón, Hernández, & Castañeda, 2004).

Even classes on design for development follow the same design process as product development in resource-rich contexts (Viswanathan, Yassine, & Clarke, 2011). While the content is changed to be more appropriate for subsistence contexts, the structure of the design process remains the same, with conceptual design and selection taking place before consideration of materials, manufacturing, and economics. Students refine their concepts using this new knowledge, but it was not incorporated into the generation of ideas. There has been considerable research into designing products that will work in the developing world context, but less on designing product development processes that will work best in resource-constrained settings.

The objective of this research is 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 more useful findings about how to construct a campus environment or curriculum to foster the development of desired problem solving skills.

2.6 Summary

Many researchers have commented on the potential impact of resources on product design, but there has been little integration of these topics. Discussions of development policy have begun to include the need to incorporate design and innovation into policy conversations. At a firm level, multiple papers have been written about how the environment firms operate in can affect their decisions. Finally, in design research, multiple experiments and case studies have been conducted on how constraints can influence the idea generation process. However, there has not been a systems model that clearly integrates these concepts, along with strategies for improving system outcomes, which are the core of this thesis and will be described in the next chapter.

3. Analytical Framework/System Model

3.1 Overview of the Chapter

Before explaining the methodology and results in later chapters, this chapter will focus on laying out the conceptual model of the study. The following will cover the conceptual model linking product design, prototyping resource environments, and private and public policy decisions. It will also include the research questions and hypotheses. The next chapter will cover models of the design process and innovation systems, as well as strategies for product design. This will give a base for the conceptual models that will be filled in with more detail and explored using data from the case studies.

3.2 System Model

This study is inherently the study of a sociotechnical system, with multiple levels and subcomponents. Systems analysis is often divided into "hard" and "soft" with hard systems being associated with easily defined systems and soft associated with messier, ill-defined ones. Checkland advocates dealing with messy socio-economic-technical systems by building a conceptual model, and then using evidence from the real world to support or to suggest changes for it (Checkland & Scholes, 1999).

The general framework of this research study is expressed in Figure 3. The participants in the system are the government, universities, firms, who can influence the prototyping resource environment via the implementation of policies. This environment influences engineers, and designers, who can apply design strategies in order to produce design outcomes (such as new products, prototypes, or designs).

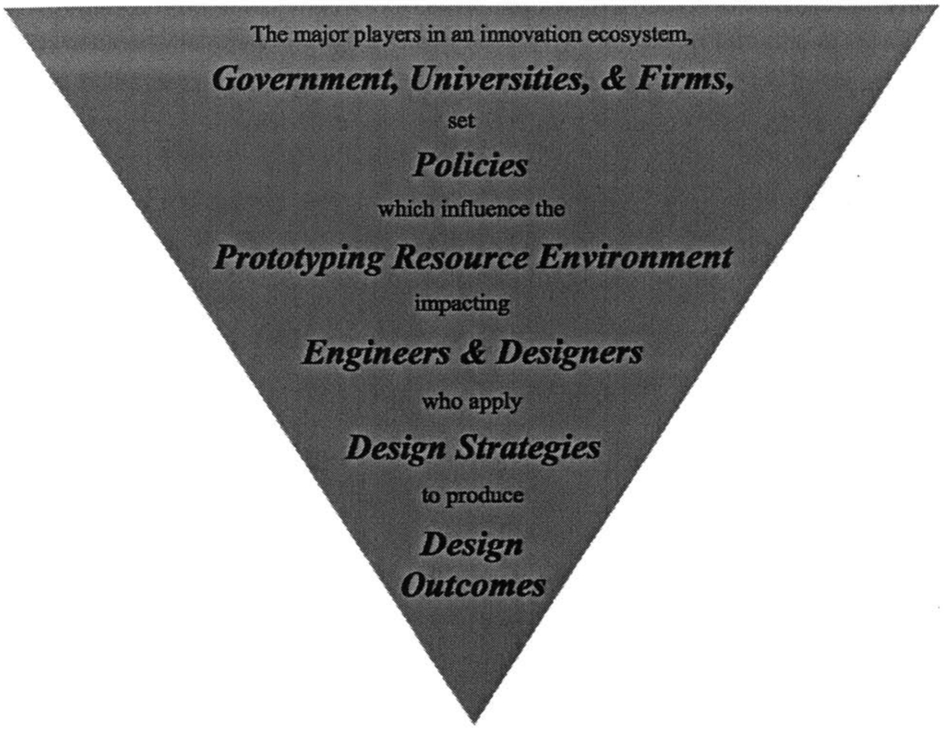


Figure 3. General research framework relating stakeholders, outcomes, and actions

By analyzing the interconnections between the subsystems, and then building back out by integrating the findings, it is possible to further understand the entire system. The majority of this chapter will focus on modeling a prototyping resource environment, with some discussion on policy instruments and design strategies, which will be covered in more detail in later chapters.

3.2.1 Modeling Product Design and Prototyping

Product design has been modeled in many ways, as a chronological process, but also as a physical process, with material and information flows over time between the actors in the system. Product development in a firm often comprises multiple divisions, which add value throughout the project lifetime. The firm also interacts with outside parties, such as users and suppliers.

Research and private sector examples have suggested that better integrating the needs and capabilities of these parties both within and outside of the firm lead to better design outcomes. User-centered design and concurrent engineering advocates argue that both techniques reduce waste and the probability of re-work of unsuccessful designs by incorporating inputs from users and manufacturing during the design process.

A smaller body of research has focused on the merits of 3D concurrent engineering, which also takes into account the supply chains, which further decreases the cost and increases the probability of successful project implementation. A simple model of this system and the design strategies is depicted in Figure 4, modified from the prototyping strategy model provided by Hughes and Cosier (Hughes & Cosier, 2001). Incorporating suppliers into the system model is an important component in order to ensure synergy, and a lack of alignment of capabilities would explain why increased high-tech investment in localized settings (such as universities) does not necessarily result in more production of high-tech outcomes.

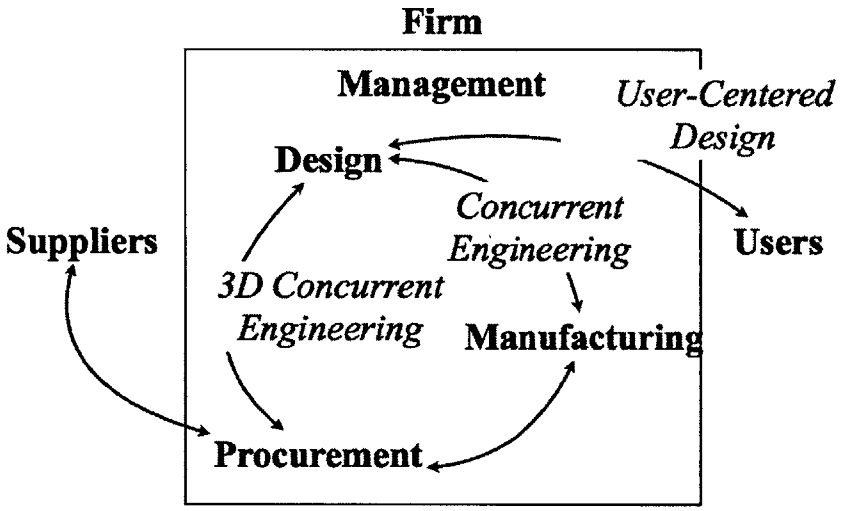


Figure 4. Model of product development by a firm

Prototyping by an engineering student can be modeled in a very similar way, as the student has to play the role of designer, manufacturer, manager, and purchaser at different times throughout the process, as depicted by the model in Figure 5, a representation created by the author. With this model, some of the many tradeoffs that students need to make in the design process are depicted. The *prototyping resource environment* affects whether the "engineering man" or the "economics man" within the student wins out during decision-making.

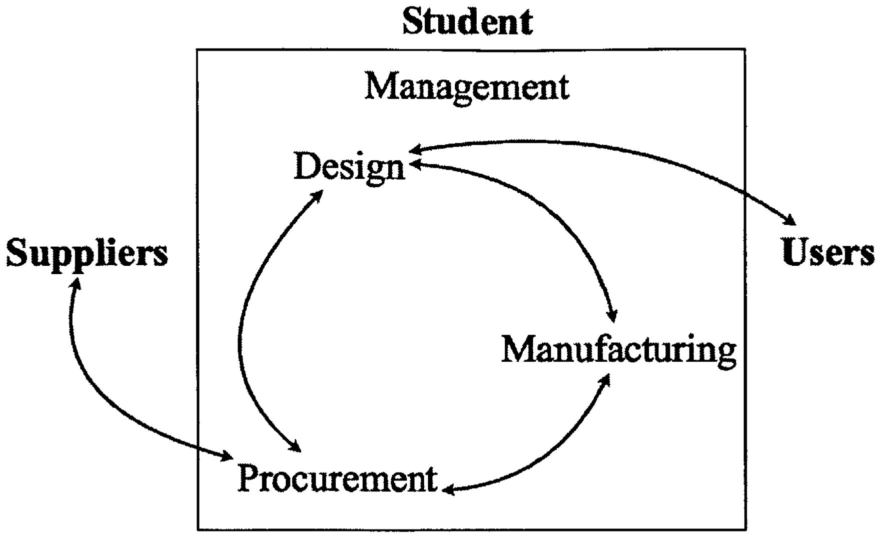


Figure 5. Model of prototype development by a student

3.2.2 Modeling Prototyping Resource Environments

Resource environments have been assessed from a variety of perspectives, from business settings to healthcare systems. These assessments usually involve specifying a system boundary to limit the scope of investigation to the components of interest. The environment itself is defined by incorporating measurements of tangible resources, through inventories and maps, as well as intangible aspects such as organizational services and linkages. The goal of these assessments is to provide a systems map of the factors that influence individuals or a group, in order to inform decision makers who may want to improve elements such as system efficiency or quality of the product.

The elements of a prototyping resource environment can be broken up into four elements, which can map to a firm, or a CAD tool. Four major metrics were isolated in order to characterize the major factors of a prototyping environment that could affect the engineering design space and ideation (Figure 6).

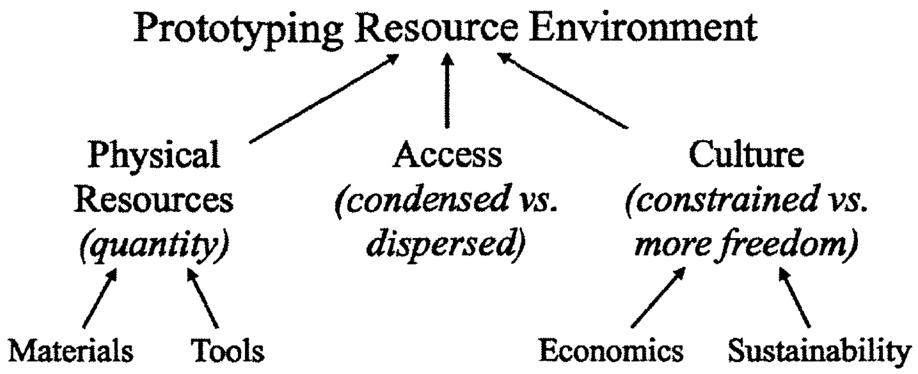


Figure 6. Factors influencing the prototyping resource environment

3.2.2.1 Materials (commodities, disposable goods)

Materials refers to both raw materials and found or manufactured objects such as car parts or household objects that are generally used for a specific purpose but could be used in different ways or modified. In a firm, these are the raw goods or components. The designer may decide to use the entire material or extract components. In a design software package, the materials would be the physical shapes that can be built (extrusion, lofting, etc.), or the library of parts that can be imported.

3.2.2.2 Tools/Equipment (capital goods)

Tools can be characterized as either used for customization or adaptation. For example, a saw is a customization tool because it allows for more choice over the alteration of the structure of the material. A socket wrench set would be an example of an adaptation tool because it helps with lack of standardization. In a firm setting this would be referred to as capital goods. In CAD software this refers to the available options for manipulating the created shapes, including cutting and drilling.

3.2.2.3 Access

Access refers to where these items are located, whether they are concentrated and all located in the shop, or dispersed and the designer needs to go to a different place to access each. How long are the lead times for procuring materials? Are they in inventory or do they need to be picked up or shipped? Access maps to the accessibility of the user interface of a design software. Are all the components stored in different files? How long does it take to access them and integrate them?

3.2.2.4 Culture

Culture refers to how flexible or constrained designers feel, which often has a financial component but may solely refer to institutional culture. In a flexible culture, failure and multiple prototypes are encouraged. However, in a constrained culture, planning and waste minimization are more highly valued. Where the environment lies on the spectrum could influence the design process and design outcomes. Financial and environmental concerns are folded into this metric because the relative weight of each factor is often personal, and not the focus of this study. The goal of this study was to obtain a general feeling of what the culture was like, not to specifically study their relative attitudes on environmental concerns or cost, which are difficult to compare objectively across settings. In a firm setting this is likewise related to budget, but it could also be related to regulation, organizational culture, or individual designer preferences. As Schrage pointed out, two firms with similar resources could have different cultures of prototyping.

3.2.3 Integrating the Models

Following Checkland's advice on how to model and explore "soft systems," a conceptual model of the system interactions was developed in order to map out the influences of the different components, as shown in Figure 7. The students are subcomponents within a university system. The university is a component of the larger economic system that also includes suppliers and users. Students can manipulate design outcomes via design strategies, universities can influence the institutional prototyping resource environment through institutional policies, and policymakers can influence the global prototyping environment through public policies. This model can also be used to represent the impact of prototyping resource environments on engineers working in firms by replacing "university" with "firm" and "student" with "engineer."

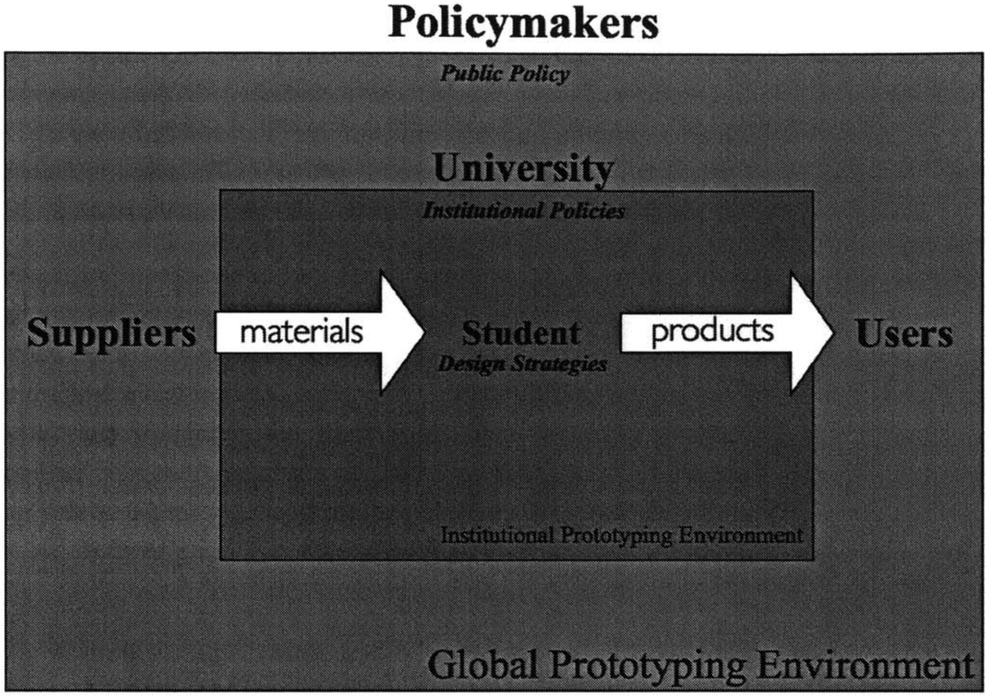


Figure 7. Systems model

The policy instruments are the knobs that system designers can turn to change outcomes in the system. These are factors that influence characteristics of the players in the system, such as suppliers, firms, universities, engineers, or users. They can also influence the environment that the players are working in, for instance via trade or industrial policies.

Following Checkland's guidance of splitting the system into a system (university), the higher-level context (Mexico), and subsystems (engineering students), this study focuses on the prototyping environment in a campus and local town *as perceived by students.* In other words, this study focuses on representing the system as it is perceived by the individual designers. However, to obtain a more balanced picture of the context, interviews with students were accompanied by site visits and interviews with professors.

3.2.4 Impact on Idea Generation

Diving further into the "design strategies" section of the model, it is possible to map out the design process over time. The dominant strategy usually involves ideating a plan for a prototype, then creating a bill of materials, and finally building a mock-up, prototype, or product, as depicted in (a) of Figure 8. This is a divergent process in the ideation stage, which converges before construction.

An issue occurs if the design environment is unfamiliar, uncertain, changing, or overly constrained. In this case, there is a high probability that the design cannot be created, and a prototype cannot be built, which would require the designer to re-visit the design stage (b).

To counteract this problem, another design strategy is to start the design process by examining the available resources, and to draw inspiration from these constraints in the ideation phase, as depicted in (c) of Figure 8.

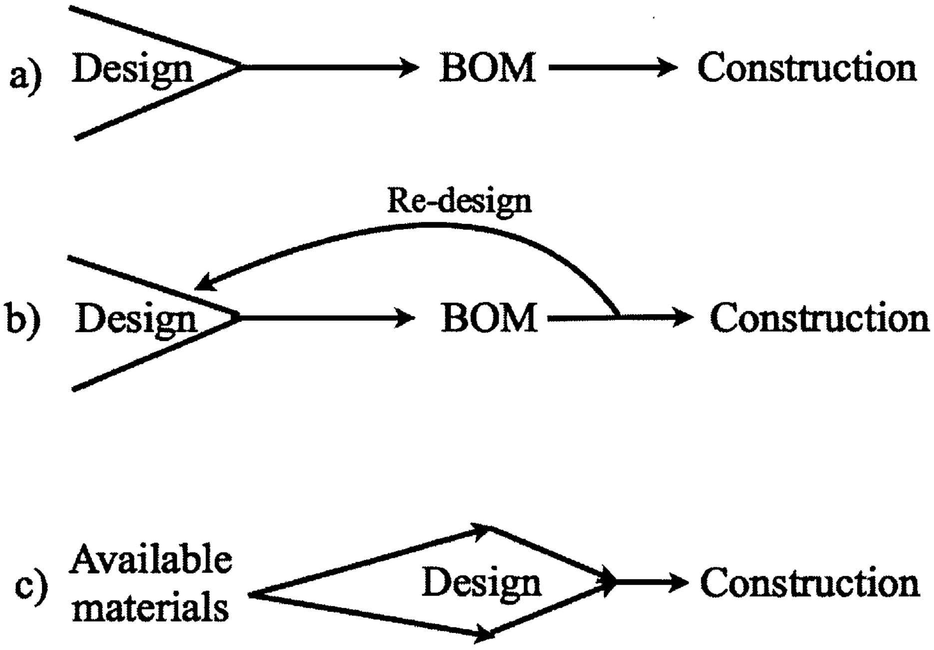


Figure 8. Design strategies

When designing in a more constrained setting, many designers often start by applying strategy a, and then realize that they have run into an obstacle, therefore resorting to strategy b. Designers who have previously encountered these types of obstacles often also include strategy c in their arsenal of design strategies when faced with a new design challenge.

3.3 Research Questions & Hypotheses

Taking the previous models into account, the next step is to incorporate real-world data in order to start to address the original research questions.

Research Question #1

How does the prototyping resource environment that students learn in influence their design decisions and processes?

> **Hypothesis #1a**
>
> Students in more resource-constrained settings will have had more experiences adapting their designs to resource constraints.
>
> **Hypothesis #1b**
>
> "Thinking inside the box" and abstraction of the design before searching for materials will be more common in resource-constrained environments.

Research Question #2

Assuming a constrained prototyping resource environment, how does the timing of information about the constraints influence early-stage design outcomes?

> **Hypothesis #2a**
>
> Knowing constraints earlier on will result in more appropriate concepts for the user.
>
> *Justification: Without free-reign, designers will focus more on user needs for inspiration.*
>
> **Hypothesis #2b**
>
> Knowing constraints later will result in more marketable designs.
>
> *Justification: More references to existing technologies that have been successful in the marketplace.*
>
> **Hypothesis #2c**
>
> Knowing constraints earlier will result in more novel designs.
>
> *Justification: Not as easily able to reference existing technologies.*

Research Question #3

Does the prototyping resource environment that students learn in influence their design outcomes when they are put into a more constrained environment?

> **Hypothesis #3a**
>
> Students with more practice working with constraints will develop more novel concepts.
>
> *Justification: They will be used to looking beyond the normal use of objects and materials.*
>
> **Hypothesis #3b**
>
> Students with more resources will develop more technically feasible concepts.
>
> *Justification: They will have had more experience with precision machining and component selection, and building prototypes with less resource constraints, which allowed them to make mistakes and learn from them.*

3.4 Summary

This chapter established a theoretical model for exploring the impact of prototyping resource environments on product design from a macro level at the public policy scale, to a micro-level of individual designers. By drawing connections between product development in a firm and the creation of prototypes by individuals, a framework was created as a basis for collecting and analyzing data within a complex sociotechnical system. The next chapter will describe the research methodology.

4. Methodology

4.1 Overview of the Chapter

This chapter will cover the details of the fieldwork that was conducted. It will explain why the methods of research were chosen and describe the research design. The later sections will cover data collection and analysis procedures.

4.2 Choosing a Research Method

The objective of the study was to explore the relationship between the prototyping environment and the design process of students. A case study was determined to be the best methodology for investigating the process of design within the greater prototyping resource context. The specific results of this study are not generalizable, as prototyping resource environments and designer's reactions to them vary around the world, however there are themes that may be applicable to other contexts.

A case study method was chosen over a general survey because the aim is not to describe product design in Mexico as a whole, but to better understand the influence of the environment on individuals, and to provide a conceptual framework that others can adapt to their own setting, i.e. to better understand a phenomenon within its context. The boundaries of this case are geographical, focusing on the campus and city, and physical, focusing on the material inputs and tools involved in the prototyping process. To provide some context for the design decisions and to account for possible differences in education, students and professors were also asked about past design projects and the design curriculum on campus.

The case was designed to explore a phenomenon observed by the author in previous design experiences. To focus data collection, the methodology was shaped around theory testing, but as these themes have not been studied before in this context, the study was also constructed to allow room for exploration. It was also decided that collecting illustrative data would be important to describe the phenomenon to people who may not have experienced design in a different context.

Within the case study, a mixed-method research design was utilized. In this case, the subjects were engineering students at two different university campuses in Mexico, and the analytical frame was the prototyping culture and design process. Results from interviews, questionnaires, and a design experiment were triangulated to investigate the influence of different factors. Both qualitative and quantitative methods were used to analyze the data.

Referring back to the main research questions, each method was chosen to address a specific issue, and different instruments were employed in order to triangulate the results. The details of these instruments will be discussed later on in this chapter.

Table 1. The research instruments were designed to address one or more of the research questions

How does the prototyping resource environment influence the design process and idea generation?	***Site Visits, Interviews, Questionnaires***
Assuming the designer is working in a constrained environment, does the timing of information about prototyping resource constraints influence design outcomes?	***Design Experiment with Web Evaluation Survey***
How can policymakers and system designers influence the prototyping resource environment and the design process?	***Interviews with Professors and Students, Questionnaires***

4.3 Research Design

This investigation involved multiple embedded (nested) case studies (Thomas, 2011; Yin, 2009). This allowed for analysis at the individual designer level, but also understanding about the similarities and differences between the experiences of students within the same campus. Interviewing professors also provided more information about the context and a different perspective on the students' experiences. Figure 9 depicts how the embedded case studies of two different campuses in Mexico fit into the general system framework described in Chapter 3.

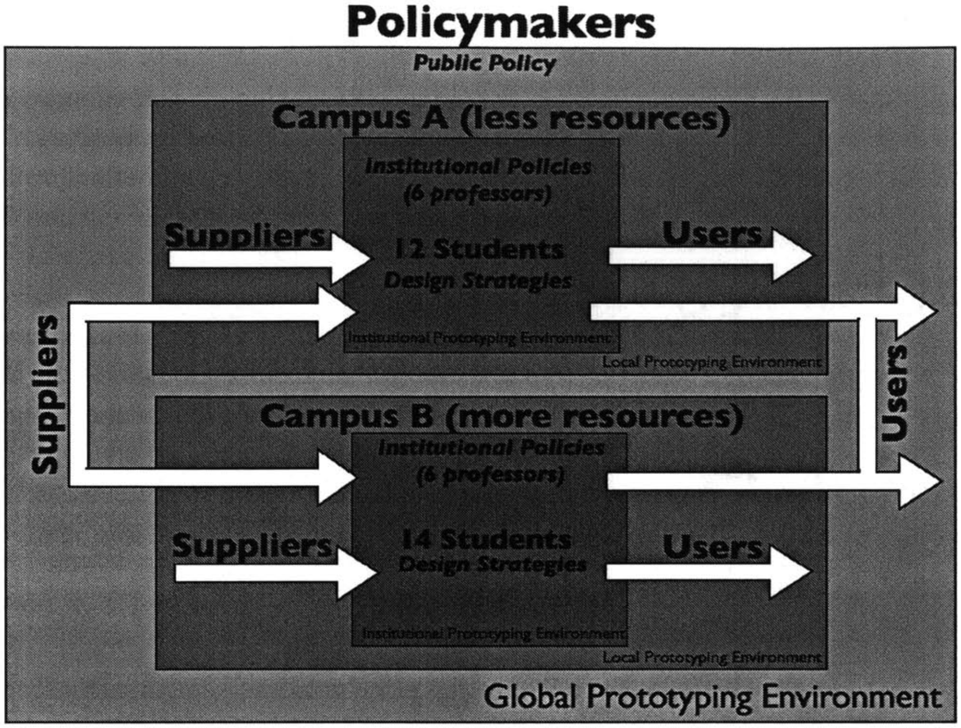


Figure 9. Multiple embedded case studies

4.3.1 Case Selection and Participants

The cases were selected to provide as large of a difference in access to resources as possible, while controlling for other variables such as curriculum and regional culture. Data collection was limited to within one university system because it has multiple campuses located across the country, all with a similar engineering curriculum but variable access to resources. The goal was to choose campuses with distinctly different material cultures of prototyping without introducing other influential variables such as institute culture, access to media or information, curriculum, or national engineering culture.

26 undergraduate engineering students were recruited from two campuses of a university system in Mexico (12 from Campus A and 14 from Campus B). 14 additional students from a third campus participated in the pilot phase of this study. They participated voluntarily in this experiment and participants were given a consent form to sign, which was also translated into Spanish. All aspects of the study, including interviews and questionnaires, were conducted in Spanish to maximize comfort of the participants and the fluidity of their written and oral responses.

Students were recruited from both the mechanical engineering and mechatronics departments because they complete similar coursework in designing mechanical systems. Given the relative simplicity of the detailed technical knowledge required for this creative design task, and the resulting designs from the pilot study with all mechatronics students, both were determined to be suitable subjects for this experiment. There is a possibility that mechatronics students would be more likely to incorporate electronic systems into their design, but the design prompt for the experiment clearly stated that details on electronic or software components were not necessary and that the designs should be mainly mechanical.

In Campus A there were twelve total participants, two females (16.7%), five mechanical engineering and seven mechatronic majors. Their education level ranged from 2 to 10 semesters completed, with the majority (8/12, 66.7%) completing 7 to 8 semesters of undergrad.

In Campus B there were fourteen total participants, five females (36.7%), two mechanical engineering and twelve mechatronics majors. Their education level ranged from 4 to 8 semesters completed with the majority completing 6-7 semesters (9/14, 64.3%).

The sample size is too small to draw conclusions about the influence of gender, major, or education on this study but no strong correlations were found.

4.3.2 Overview of Instruments

The instruments were designed to gather information at a campus, participant, and design level, as shown in Figure 10. The campus level provided a context to interpret the accounts of the students, and the web survey provided an objective evaluation of the designs produced by the participants during the experiment.

Multi-method research design

campus	student	sketch
	Entry Questionnaire	
Field Visits	*Design Experiment*	*Web Survey*
Interviews with Professors	*Exit Questionnaire*	
	Interviews with Students	

Figure 10. Research instruments used and their target scope of analysis

Each tool was designed to address a piece of the general research framework, as shown in Figure 11.

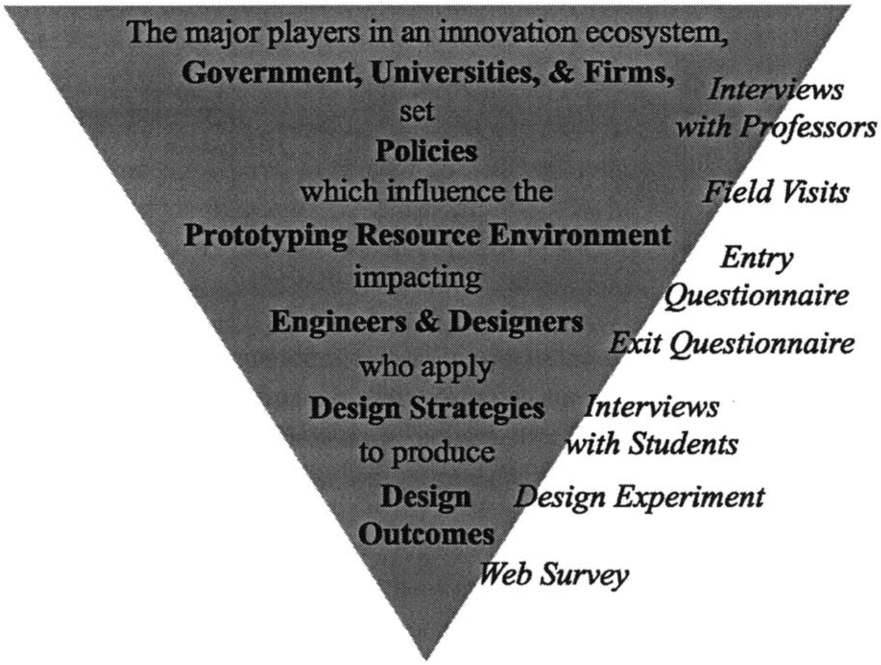


Figure 11. Integration of research instruments with the system framework

4.3.3 Validity and Reliability

Construct validity: Multiple instruments were used to test each metric and to develop "chains of evidence" that would support the conclusions.

Internal validity, Literal Replication, & Theoretical Replication: Tests were run with multiple students in two different campuses.

Reliability: A written protocol was used for conducting fieldwork, including a structured protocol for the design experiment portion and a semi-structured interview format.

4.3.4 Field Observations

Site visits are a major component of researching the material culture of any setting. While it is possible to ascertain some details of the prototyping environment from lab descriptions and photos of prototypes on the institution's website, field observations help provide a more complete picture. The author visited the primary lab, student workshops, and manufacturing cells on campus.

4.3.5 Biographical and Prototyping Environment Questionnaire

Students were asked to complete a questionnaire about the extent to which certain factors influenced their design decisions. This information provided a quantitative metric for understanding how students rank the relative influence of factors related to the prototyping environment vs. other aspects that are normally associated with design.

Previous studies have suggested that the perceptions are more important than facts, especially for understanding behavioral responses. Therefore the data collection tools were designed to capture the student's perception on the importance of different factors, rather than to create a detailed inventory of available materials. Given that the perception of material resource adequacy can differ greatly from absolute resource levels (Hoegl, Weiss, & Gibbert, 2010), other factors were included in the questionnaire such as feedback, assembly, aesthetics, and personal machining ability to better gauge the relative weight of each factor in participant's minds during the design process. Copies of the questionnaire and the rest of the experimental materials are included in the Appendices.

4.3.6 Sketching Exercise

4.3.6.1 Warm-up

Participants were given a Torrance circle test (Torrance, 1966) and were told that they had one minute to sketch as many pictures as they could, using the circles on the page. The goal was to warm them up for the design experiment. This type of Torrance test was chosen over other formats, such as those that ask participants to brainstorm alternative uses for an object, in order to avoid priming the students for the following sketching exercise.

4.3.6.2 Design Task

In each experimental case, the students were given a prototyping environment that was more constrained than what they were used to, and were asked to sketch concepts for prototypes that they could build, and that would address the needs of a specific population in Mexico (shopkeepers physically disabled due to diabetes). Translated copies of the experimental materials are included in the Appendices. A more realistic design prompt was chosen over an abstract prompt because the researcher felt that it would be more engaging for engineering students and that the results would be more relevant to practicing engineers. For their designs, participants were constrained to a list of raw materials, components, and found objects (plus standard fasteners) and told they could not use advanced manufacturing equipment such as CNCs and lathes.

In a way, this design experiment could be looked at as a form of "concurrent" design or design for manufacturing, where the design of a product is influenced by the need to fabricate a physical prototype of it given the materials, tools, and processes that are available. The traditional progression advocated by most researchers and educators is to generate ideas using divergent thinking, and then evaluate, select, expand, test etc. those ideas. However, the more constrained prototyping resources are, the less adequate this method may be, because substantial re-design may be required to build the same design using the available materials, and therefore it would be beneficial to incorporate knowledge of the available prototyping materials early on in the idea generation phase.

A virtual prototyping analogy for the list of materials that the participants received would be a library of components that can be recombined, decomposed, and physically modified. Some electrical components were included but participants were told to focus on the physical design of the device rather than to spend time on developing the electronics or software design. The set of objects was chosen to allow for a range of design possibilities without being exhaustive. The found objects ranged from simple to complex, and included objects both from similar and distant contexts compared to the design prompt. All materials were specifically chosen to provide new design functions, and the found objects were selected based on their potential to provide new forms, power transmission, energy storage, and other complex mechanisms when decomposed. Care was also taken to select materials based on the participants' likely familiarity with the objects and the feasibility of modifying the objects using typical tools. The mix of materials reflects the types of prototyping materials that are available in many areas of the world.

This type of design challenge was chosen for a number of reasons. Considering available resources in the idea generation phase is suggested in product design theory, especially in concurrent engineering, of which students building their own prototyping is a prime example, but little has been done to explore exactly when this information should be incorporated into the design process. In systems design, sometimes starting from scratch is impossible and the best way to add value is to explore modifying and recombining existing components. In a more general sense, this design exercise tests a student's ability to view the opportunities inherent in a small set of resources. It also tests their ability to adapt to new situations, a simulation typical of when either a design project is moved to a different resource environment or when resource environments are volatile and uncertain.

A sketching challenge was chosen over physical prototyping because it required less resources and time to complete. From discussions with engineering students and professors in Mexico, this also seemed to be a more realistic design process for design in resource-constrained settings. Designers often have mental information about what is available or can visit websites or stores but they tend to sketch first, and create a list of what is needed before buying supplies and there are few supplies besides scrap wood or metal available on campus for student use. While designs are re-worked as learning occurs during physical fabrication, designers tend to make most of their design decisions in the sketching and CAD modeling phase, and focus on building one prototype at a time.

Taking into consideration the results of the pilot study, a user profile was incorporated into the final round of experimentation. User profiles, also known as personas in user-centered design, include a picture and short biography of the target user and pictures of sample shops. User profiles help engineers and designers focus on a common vision of who the customer is and help them feel more connected to the user while designing (Courage & Baxter, 2005; Miaskiewicz & Kozar, 2011). A target user based in Mexico was selected in order to increase familiarity with the user. The setting of a small store was chosen because these types of stores are widely present in Latin America and students (who are mostly from cities) would therefore have an easier time imaging potential needs, compared to a different user, such as a farmer.

4.3.6.3 Variables

Two different experimental conditions were applied at random:

Group 1: Given 20 minutes to generate ideas that satisfy the design prompt, with no material restrictions. They were then given a constrained set of materials and told that they had 20 more minutes to generate ideas.

Group 2: Given 40 minutes to generate ideas that satisfy the design prompt. They were given the same list of materials as the first group, but at the beginning of the session.

The experimental treatments were designed to simulate two methods of design, where each group has the same theoretical "box of stuff" to work with to address the design challenge but the timing of when they receive this information varies. Figure 12 depicts the experimental treatments.

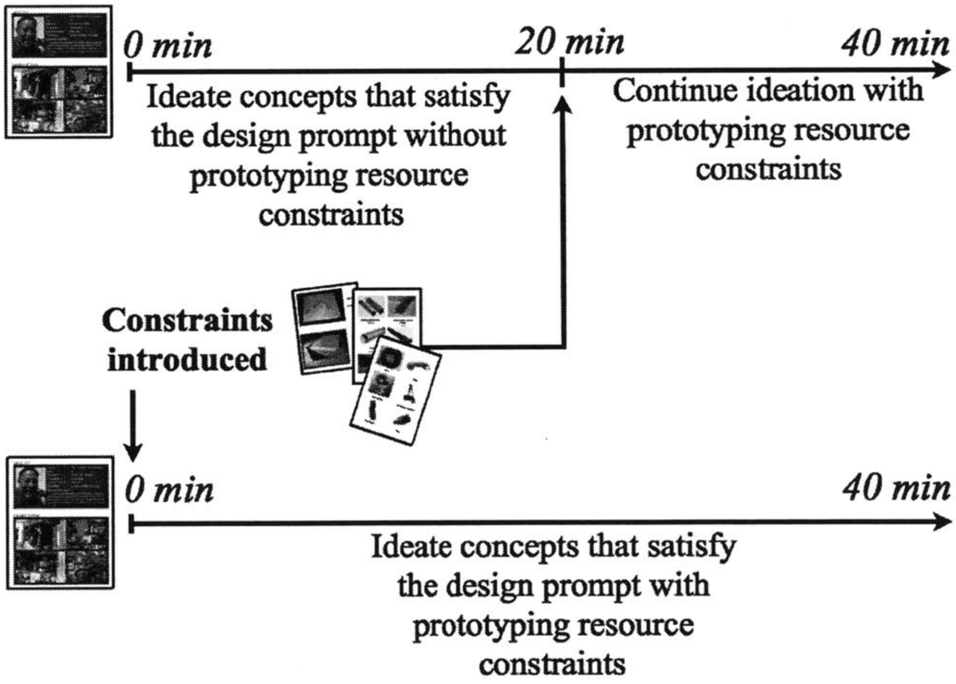


Figure 12. Experimental treatments. The top schematic depicts the experimental process for Group 1 and the bottom depicts Group 2. Group 1 is expected to create more technically feasible and marketable designs. Group 2 is hypothesized to create more novel and appropriate designs.

4.3.6.4 Equipment

A Livescribe notebook and pen was used to record the ideas generated by each participant, as well as the interviews. This technology allowed for the capture of idea generation over time, and provided both a physical and digital copy of each design and user experience, without requiring an external audio or video recorder, which could have been more distracting to the participants.

4.3.6.5 Procedure

Participants were given 40 minutes to complete the exercise and were informed how much time they had left every 10 minutes. The group that was interrupted halfway through with a constrained resource list was not informed ahead of time that there would be a change in the design prompt. The timer was paused for all participants as they read over the design prompt, and therefore all had an equal 40 minutes of idea generation time.

The participants engaged in this experiment individually. They were randomly assigned to two treatment groups. Both groups were given a preliminary questionnaire to fill out, indicating their prototyping experiences. Afterward the sketching exercise, both groups were given identical attitude surveys.

A protocol analysis was rejected due to a number of factors. Given the uncertainty of conducting a design study in a different culture, and because such experiments are not common in Mexico, the researcher decided that it would not be worth the added discomfort. Schooler and Melcher found that conscious verbalization inhibited the unconscious linkages needed for creative insight, therefore protocol analysis was rejected because creative, unconscious design was determined to be more impertinent to the study (Schooler & Melcher, 1995). Questionnaires and interviews were incorporated to capture conscious thought of participants.

4.3.7 Individual Interviews

After the design experiment each student was interviewed for around 30 minutes, using a semi-structured format. The interview commenced with a discussion about the projects that they listed in the biographically questionnaire to warm them up and identify potential opportunities to explore the prototyping environment metrics that are outlined in previous chapter. The goal of the interviews was to find out what their design process was and how or if design for the prototyping environment or supply chain factored in. The objective was also to understand if and how signals from the prototyping environment influenced the conceptual design process and caused students to deviate from the traditional top-down, divergent to convergent, process. Discussions centered around previous prototypes not to necessarily compare and contrast the previous outcomes developed by students, but to give an anchored context for their responses on how the prototyping environment affected their design process. Learning about the types of prototypes that students created also provided some information about the type of design knowledge, materials, and tools that would be required to make them and to confirm that all participants had similar background experiences designing because prototyping methodologies may be different depending on the types of products.

4.4 Data Collection

4.4.1 Pilot Study- March 2011

This pilot study was conducted at one campus in Mexico in the spring of 2011. 14 students at the undergraduate and master's level participated in the study. All interviews and design experiments were conducted in Spanish and all necessary materials were translated and confirmed by a bilingual Mexican beforehand.

The interview structure was found to be effective but some changes were made to the experimental design after the pilot round. The original prompt was to develop a product for a disabled shopkeeper in a developing country. However, the range of solutions addressed a variety of potential user needs and therefore were more difficult to compare. There was concern that the participants may have had different mental images of the "developing country" context, which could have influenced their design choices.

To address these concerns, a user profile was added with information about a target user such as age, budget and occupation, and included photos of example shops where the target customer could work, to allow designers to understand the types of contexts their device would need to work in. The target context was also changed to small stores in Mexican cities, which the participants are all familiar with. A specific disability was chosen along with a context that is found across Latin America to help encourage engagement with the task, which is supposed to help design outcomes. While both the target context and user were individually familiar to the designer, the combination was chosen for the design challenge to encourage them to tackle a problem that has not be adequately addressed before. A lower target price point was maintained to encourage participants to think of designs beyond the expensive existing solutions for disabilities or commercial settings.

The exercise was also changed to make the wording in each experimental treatment as identical as possible, to avoid potential wording effects. It was also found that some participants provided more annotations than others, which may have had a large influence on the number of designs they generated. To ease comparison and reduce time required for students to annotate their sketches, a checklist of elements to include was added and the desired level of detail was clarified. In the pilot study, participants were given a target range of 3-5 ideas in order to encourage them to develop more than one idea, but it is possible that this time pressure influenced their idea generation. The design prompt was therefore changed after the pilot study to request as many ideas as possible rather than giving participants a target range.

4.4.2 Two-Campus Comparison- August 2011

The final version of the experiment was conducted on two campuses with a total of 26 participants, resulting in 109 sketches. Six professors in each campus were interviewed, which provided a broader perspective. The interviews and on-site observations revealed that the two campuses were similar in almost every respect except for their prototyping environments.

4.5 Online Evaluation Survey

4.5.1 Design

The goal of the web survey was to obtain an outside viewpoint of the quality of the design concepts. Every page of the survey included a note to the evaluators to remind them to base their evaluations on the general design concepts, not the construction or materials used in the prototype, because the objective of the study was to determine if they thought that the product in general was inventive, not if the inventor used a certain material in a clever way.

Five metrics were chosen for evaluation of the concepts: novelty, appropriateness for the user, technical feasibility, marketability, and clarity. Given the large number of sketches (109) and the need to evaluate certain characteristics of each sketch in order to give a fair comparison, a 3-point scale was chosen. A smaller scale was chosen to reduce the time required to complete the survey, to force evaluators to make a decision. The final options were "in disagreement," "undecided," and "in total agreement." Prototype trials showed that evaluators felt that the majority of sketches fit into one of the three categories and agreed that having three categories was better than four overall.

The order of the five statements was the same for each sketch in order to reduce errors and minimize the time required to complete the survey. Evaluators were informed of the target user and general requirements of the prototypes, but were blind to the purpose of the study and information about the research variables and most identifying factors of the inventors.

There have been some concerns in the literature over the ambiguity of metrics in design research. The wording of the metrics were chosen after an examination of the literature and discussions with contacts in Mexico over which word choices would be clearest after translation into Spanish. The translations were discussed with designers and non-designers, bilingual Spanish speakers to ensure that the wording was clear.

It was decided to target professionals with experience in Mexico because their perspective of what is innovative or appropriate in Mexico due to culture and technological context is most likely different from what American designers with no experience in Latin America would decide. Given the technical and market components of the metrics, the biographic questions were structured to capture information on how qualified a given evaluator would be to judge each of the five metrics. For this reason, standard questions about age and occupation were included and a question was added about how long they have lived in Mexico or a Latin American country and if they knew someone in a situation similar to the user, in order to assess familiarity with the target users and the market. Similar questionnaires sent to laymen have resulted in questionable evaluations of technical feasibility. This questionnaire design would allow for capturing a wider range of data on the qualifications of an evaluator in order to take advantage of the expertise of a larger group of evaluators. Targeting Latin American engineers as evaluators was also a natural choice as the annotations on the sketches were written in Spanish.

One large concern was that the evaluations of a sketch would be influenced by the previous concepts. There was also concern about evaluator fatigue for sketches that appeared later in the survey. Therefore the length of each group of sketches was determined by prototype trials. It was found that fatigue started after evaluating around 40 sketches in a row. It was decided to give each evaluator a batch of 30 sketches to evaluate, which were randomly drawn from the entire 109 for each evaluator. Evaluators were assured that their participation was voluntary and that they could decide to not answer a question or leave the survey at any time.

The link to the description page and survey was posted on Amazon's Mechanical Turk website. Studies have suggested that this method for collecting evaluations is no less reliable than a survey of a typical subject pool (Paolacci, Chandler, & Ipeirotis, 2010). Another website was created that described the design prompt and instructions for the survey, with a link to the survey that would open in a new window, in order to allow evaluators to refer back as necessary. 149 people rated the ideas, resulting in about 30-50 ratings per sketch. The average compensation was $1.83 per hour of evaluation.

4.5.2 Survey Participants

The evaluators of the sketches were 42% female and 58% male. 44% were between 18 and 24, 28% between 25 and 29, 13% between 30 and 39, 11% between 40 and 49, and 4% greater than 50 years old. 40% terminated schooling at the undergraduate level, 10% had a Masters, and 4% had a PhD.

29% of respondents had not lived in a Latin American country, 27% had lived there for more than 10 years, and the remaining evaluators had lived in a Latin American country for less than 10 years. Studies on cross-cultural variation of creativity have suggested that cultural values and domain expertise could influence how people value products. Given that each culture has its unique way of judging creativity, there are often biases introduced when someone from outside the culture attempts to judge creativity (Lubart, 1990). Since language can also play a role in the judgment of ideas, the designs were both created and evaluated in Spanish, to avoid the influence of linguistic differences. Evaluators with experience in Latin America were also targeted because they are in a better position to evaluate the merits of the designs in the proposed contexts.

30% of respondents are currently or had previously worked as an engineer or designer. 33% of total respondents had worked in product design, but the majority had 3 years or less of experience. 32% of evaluators knew someone in a situation similar to the user in the design prompt.

4.5.3 Novelty

There are multiple ways to define novelty, but in this case evaluators were asked if they agreed with the statement, “The concept is original and uncommon.” The goal of this metric was to understand where the designs mapped out on the spectrum of routine, incremental, and innovative design. The decision of which type of design is a better option is ultimately a decision that the firm or university must make given internal resources, the market context, and educational goals, but generally innovative design is valued in a competitive economy because it allows the firm to be a first-mover in a new market.

This type of survey is an adequate way of evaluating the novelty of the products because as some theorists have suggested, the creativity of a product is a social judgment (Amabile, 1983). There have been some studies that suggest that conceptions of creativity and the relative value of novelty and appropriateness in determining creativity may differ across countries due to national culture (Lubart, 1990; Paletz & Peng, 2008). An in-depth comparison of novelty evaluations by Mexican and American engineers would be an interesting topic for a future study.

4.5.4 Appropriateness

Evaluators were also asked to indicate how much they agreed with the statement, "The concept is appropriate for the user and the context described in the design prompt." There is extensive literature on the importance of user-centered design, especially in the context of design for low-income customers. Given that the framework of the design simulation was that the participants needed to develop a product for a specific market, it was important to know how well the designs fit the user's needs and context.

4.5.5 Technical Feasibility

In product design it is also important to isolate technically feasible designs that could be actually implemented. It is possible that participants developed a novel idea that was appropriate for the context, but technically infeasible due to the laws of physics. The statement in the online survey was "The concept is technically feasible."

4.5.6 Marketability

While appropriateness is related to whether the product addresses a user need and context, a product is marketable if someone will buy it. This is related to knowledge of buying patterns and consumer culture, because while a product may address user needs, that does not necessarily mean that consumers will decide to spend money on it. This could be due to change in behavior required, social norms, or other aspects of the product such as user interface, security, autonomy, flexibility, etc. that may influence purchasing decisions. This is obviously an important metric for selecting ideas that will be successful in a for-profit business model.

The phrase used in the evaluation can be translated as, "The concept is marketable."

4.5.7 Clarity

Finally, the evaluators were asked to indicate how clearly they felt the concept was expressed, or how much they agreed with the statement, "The concept is clear (well communicated)." There have been studies that suggest that the clarity of sketches has an impact on how people evaluate the ideas expressed, with varying conclusions (Tsai, 2011). Asking about clarity instead of sketch quality helps to more accurately compare concepts generated by participants with different styles, as some focused more on developing detailed sketches while others used more annotations.

Ideally, a design will have high scores on each of the five metrics with low variability among the evaluators. In a real business situation, there may be merits to pursuing incremental innovation, or a design that is appropriate but not novel, so each individual metric will be explored first, and then the highest scoring designs overall will be plotted.

4.6 Summary

Multiple methods were used in this study in order to better understand the students' product design process within their prototyping context. Each method was designed to focus on a particular aspect of this relationship, and the multiple types of qualitative and quantitative instruments allowed for a richer picture of both comparable details and information about why certain results may have been found.

5. Results & Discussion

5.1 Overview of the Chapter

This chapter will provide a brief overview of some of the results from these multiple embedded case studies. The first sections will focus on comparing the prototyping resource environment of each campus and discussing its effect on the product design process of students working in that campus. The following portion will present the results of the design experiment and examine how the timing of constraints, along with the student's home prototyping environment may influence design outcomes.

5.2 Prototyping Resource Environments

Campus A is located in central Mexico in a city with a population of around 1.5 million. There are also a number of industrial suppliers nearby. The campus has one prototyping lab and a new industrial design lab was being built in a technology park close by at the time of the interviews. Students pay for the majority of prototypes.

Campus B is also located in central Mexico, in a city with a population of around 800,000 that is home to numerous industrial parks and factories, and an economic growth rate above the national average. The campus itself had three spaces with prototyping equipment, and the institution pays for the majority of prototypes.

Before the experiment, participants were asked how much sixteen different factors influenced their design process, on a seven-point scale. For each campus, the scores for each factor were averaged and sorted from most influential to least, as shown in Table 2.

Table 2. Factors influencing the design process (factors related to the prototyping environment are in bold). Note the difference in ranking of feedback from users and colleagues.

	Campus A	Campus B
1	**Budget**	Feedback from professors
2	**Access to manual tools**	**Access to manual tools**
3	Personal machining ability	Limited time
4	Limited time	Feedback from users
5	**Access to raw materials**	Feedback from other engineers
6	Assembly	**Access to machine tools**
7	**Access to machine tools**	**Budget**
8	**Time to obtain materials**	Personal machining ability
9	**Access to basic electronics**	**Access to raw materials**
10	**Access to mechanisms**	Assembly
11	Feedback from other engineers	**Access to basic electronics**
12	Feedback from professors	**Access to mechanisms**
13	**Access to advanced electronics**	**Time to obtain materials**
14	Feedback from users	Aesthetics
15	Business plan	**Access to advanced electronics**
16	Aesthetics	Business plan

Three of the top five factors in Campus A and one in Campus B were related to the prototyping environment while 7 of the top ten most influential factors in Campus A were related to resources, compared to 4 out of ten for Campus B. There was also a large difference in the relative ranking of feedback from professors, other engineers, and users in each campus. The relative ranking of budget and time required to obtain materials are also considerably different. However, the ranking of access to manual and machine tools and the influence of the business plan and limited time to build prototypes were relatively consistent between the campuses.

5.3 Impact on Product Design Process

Students were also asked to describe their design process during past projects. The majority of students described a typical design process:

1. understand the user/problem specification
2. generate ideas
3. choose the optimal and refine the ideas
4. make sure it works with the materials/tools
5. sketch out subsystems
6. test and refine
7. document

Even if the design is similar to past prototypes, students in Campus B tended to buy their own materials rather than dismantling an old prototype. Many students expressed that they have access to almost everything they needed on campus or locally, and did not have difficulty finding anything they needed, although sometimes they would need to go to Mexico City for a more complex electronic component. Many students expressed the desire to create the most elegant, simple solution that would address the task.

While students in Campus A reported a similar design process, they also discussed times when they needed to (or wanted to) follow alternative design processes. This included re-designing after they found out that the original design would not be feasible given budget, resource, or time constraints, and starting idea generation while explicitly taking constraints into consideration. Students in Campus A also mentioned more instances of replicating a more complex or high-tech idea with locally available, simpler parts. For example, one student described a design situation where they needed a certain type of camera, but it would take 3 months to arrive so they decided to make their device with just sensors. However, the sensors they had did not have the range they wanted so they bought a bunch of simple sensors to make a more complex one.

Some students in Campus A also described their strategy to keep an open mind during the early design stages, and to take inspiration from the materials available to them.

Figure 13 depicts the differences in the design processes of each campus. The findings from the interviews were consistent with the hypotheses related to the first research question, as described in section 3.3.

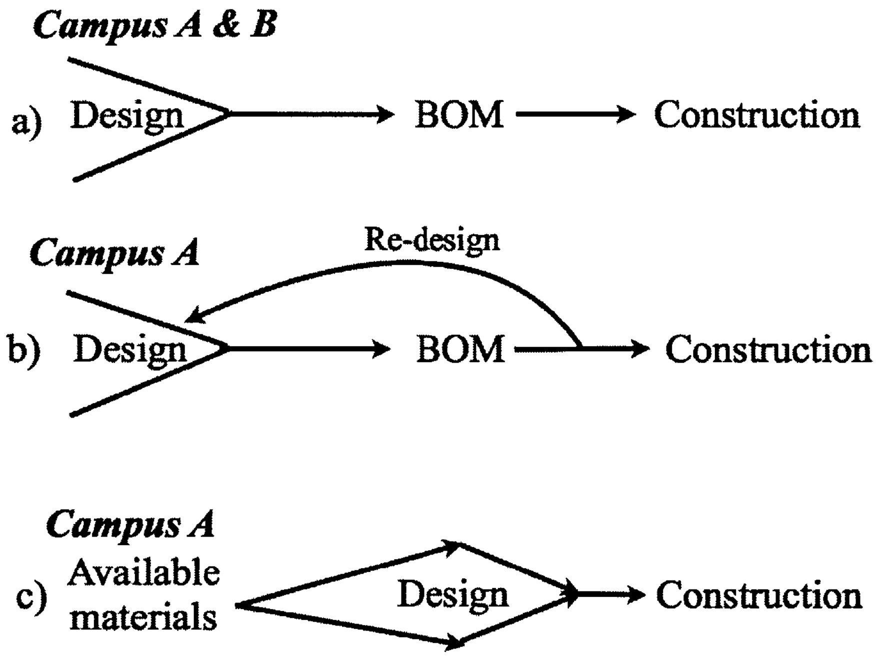


Figure 13. Design processes followed in each campus

5.4 Impact of Timing of Constraints on Idea Generation

The participants in each campus were also asked to complete a design exercise, which included two experimental treatments. In the results shown, each treatment was assigned a name, as depicted in Figure 14.

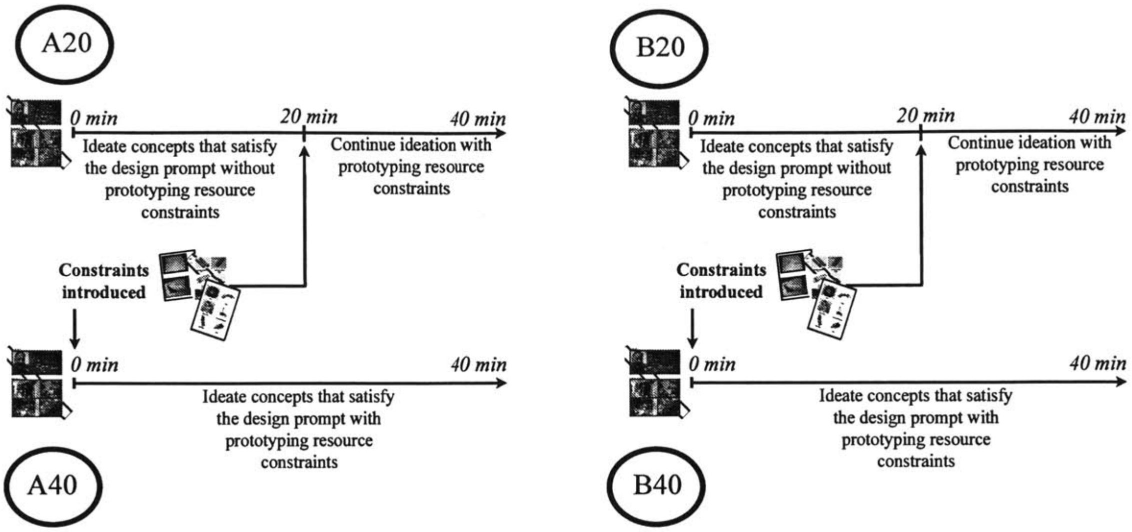


Figure 14. 2x2 Experimental design

5.4.1 Quantity

B20 generated the highest total number of ideas on average, but there was a larger difference between the total number of ideas in B20 and B40 than the ideas generated in A20 and A40. B20 also generated more ideas than A20 when they were unconstrained. Group A40 generated the greatest number of constrained concepts (4.3), followed by B20 and B40 equally (2.7) and A20 (1.8). The data suggests that there is no effect of timing on the number of ideas generated in the constrained condition in Campus B, but there is an effect for Campus A.

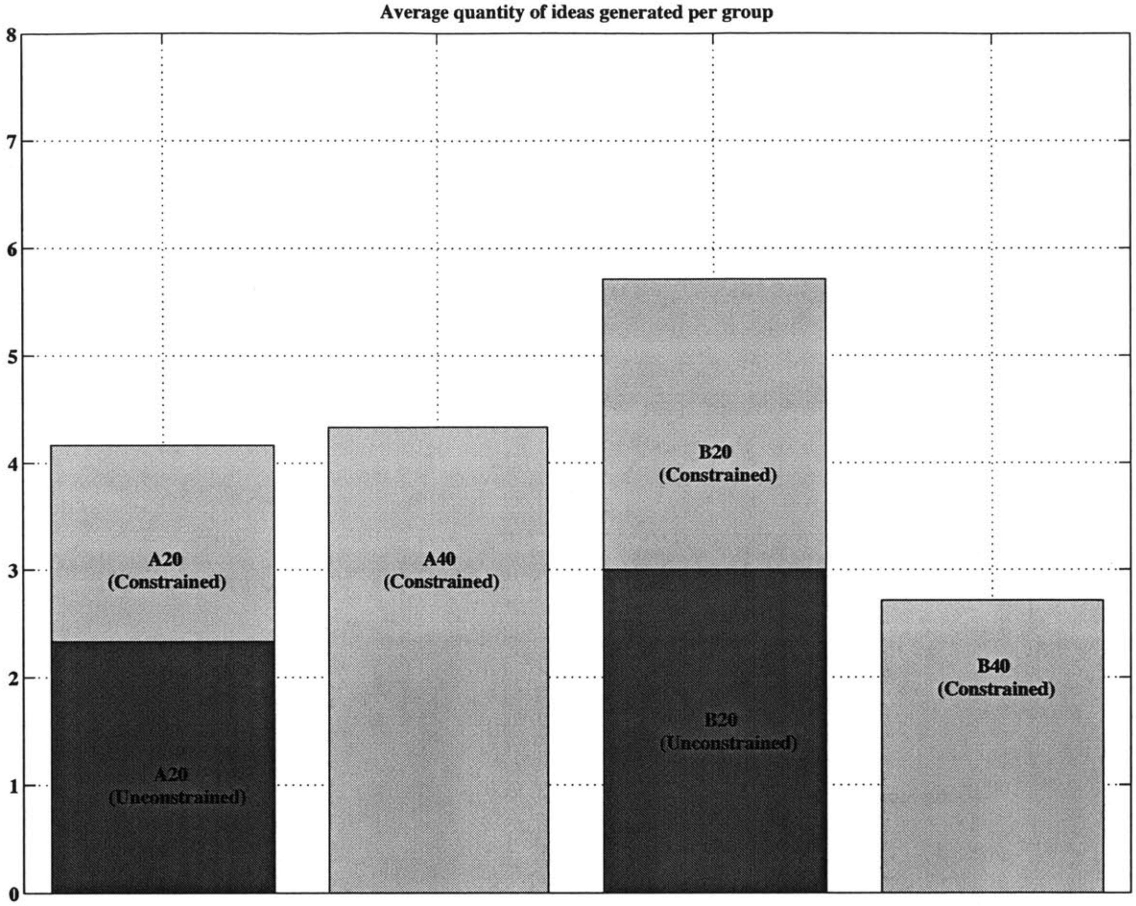


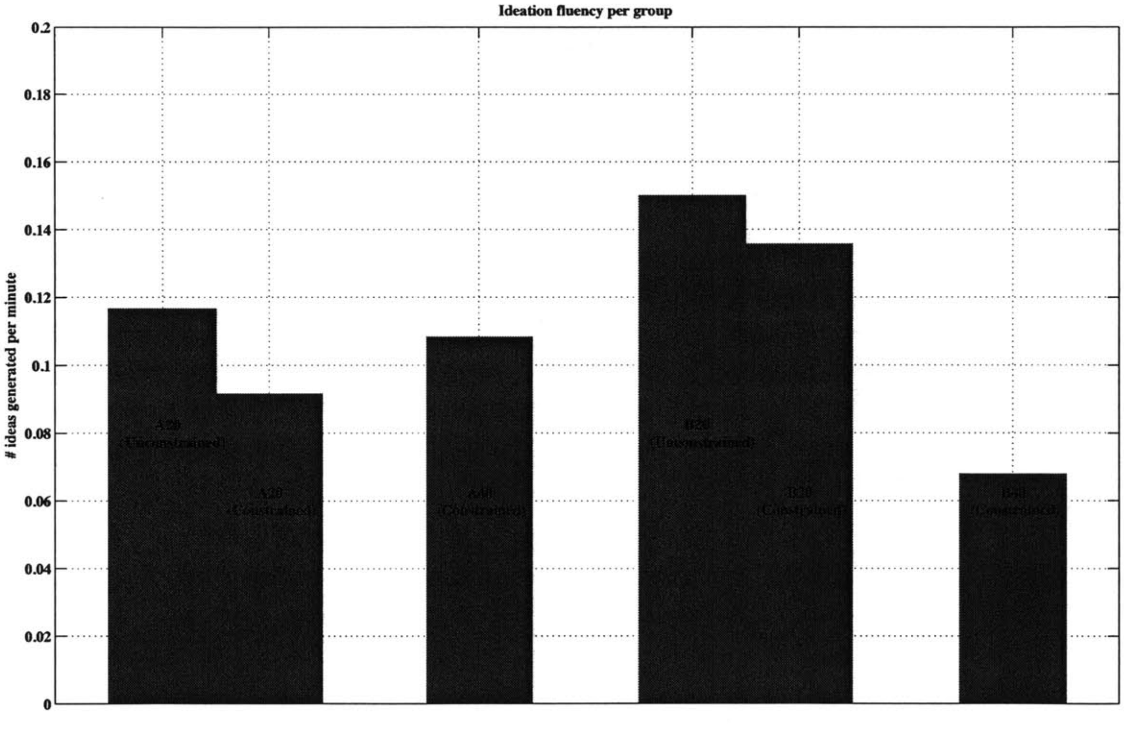
Figure 15. Average quantity of ideas generated during the exercise. It is interesting to note that the B20 group produced on average the same number of concepts in half of the time as the B40 group, which may suggest that having less constrained ideation beforehand improves idea fluency for that particular population.

A two-way ANOVA analysis of the quantity of sketches produced while participants were constrained revealed statistically significant interaction effects (p=0.0477). Campus A produced more sketches than Campus B when they were constrained at the beginning, while Campus B produced more sketches than A when they were constrained halfway through.

5.4.2 Idea Fluency

Another metric for understanding idea generation is to look at the rate at which the participants generated ideas.

On average, participants in B20 generated ideas at a rate 29% faster than A20 when they were not constrained by prototyping resources. Both generated ideas at a slower rate once they were constrained (-9.5% for B20 and -21% for A20). When they were constrained, B20 generated ideas at the fastest rate out of the four variable conditions, and twice as fast as the B40 group, which had the lowest ideation fluency out of the four. For Campus A, the opposite condition was associated with higher idea fluency, as A40's average ideation fluency was 18% faster than A20's.



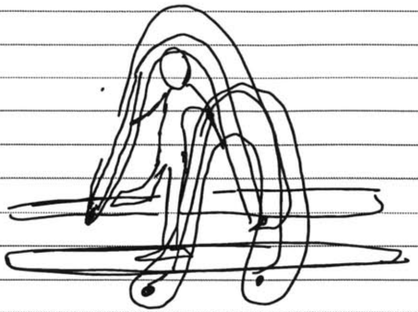
A two-way ANOVA test revealed a significant interaction effect (p=0.0323). While the sample size is too small to conclusively describe design in general, this does raise some interesting questions. The data suggests that Campus A generated constrained ideas at a relatively even rate regardless of when constraints were introduced, while there was a definite jump in ideation within constraints for Campus B when constraints were introduced halfway through. When students were asked to design with constraints, the rate of ideas generated by Campus B was positively correlated with having divergent ideation beforehand, while there was not a large difference for Campus A. This could be explained by their existing prototyping environment and design processes. Since the students in the B40 group were both in a more constrained environment and forced to follow an unfamiliar design process, they were pushed furthest off of the "path of least resistance" which could explain the longer time spent on each concept. Students in Campus A were used to following a variety of design processes, so therefore the imposed design process did not have as large of an effect on those participants.

5.4.3 Novelty

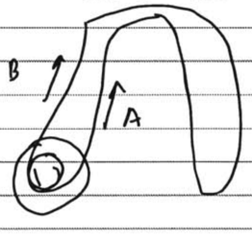
5.4.3.1 Top 10 Most Novel Designs

For the novelty portion of the evaluation, evaluators on Mechanical Turk were asked how much they agreed with the statement, "The design is original and uncommon." Out of the top 10 most novel sketches generated under constraints, 30% were created by group A40, 50% by B40, and 10% by both A20 and B20. 70% were created by participants who received information about the prototyping constraints at the beginning. The highest scoring sketches were generated by a variety of participants, and therefore there was not one dominantly creative participant. These results are consistent with hypothesis 2c and prior findings by other researchers that designers generate more novel ideas when forced off the path of least resistance, while the participants in the group that was constrained halfway had more freedom to reference existing technologies early on and adapt them to the constraints.

An example of a design that scored highly in the novelty metric is a pair of skis attached to pulley systems to propel the user forward.



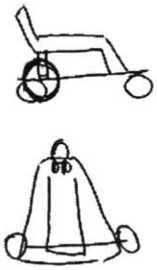
Sistema de manivela



Si usuario jala A ,
adelante
B, atrás.

An example of a design scoring lower on the novelty metric is the skate-chair, which is essentially a reclined wheelchair.

Skate-chair!



Silla en forma de tric- .
q cuenta con 3 ruedas,
las 2 posteriores se encuentran
unidas por un eje. y son
más grandes que la delantera.

- se utiliza ruedas de bicicleta. ~~adap~~
  que son impulsadas manualmente.
- la silla es plástica y se añade una base de plástico.
- para unir los componentes se usa tornillos.

5.4.3.2 Novelty of Designs Produced Per Group

First, for every participant, the scores of all of the designs produced per experimental group were averaged. After an ANOVA analysis of the sketches produced while students were constrained, statistically significant Campus effects were found (p=0.0357). On average, Campus A produced more novel results while constrained than Campus B did, which is consistent with hypothesis 3a. Interestingly, both campuses produced designs with similar average novelty when they were constrained at the beginning, while being constrained later had a positive effect on Campus A and a negative effect on Campus B (Figure 16).

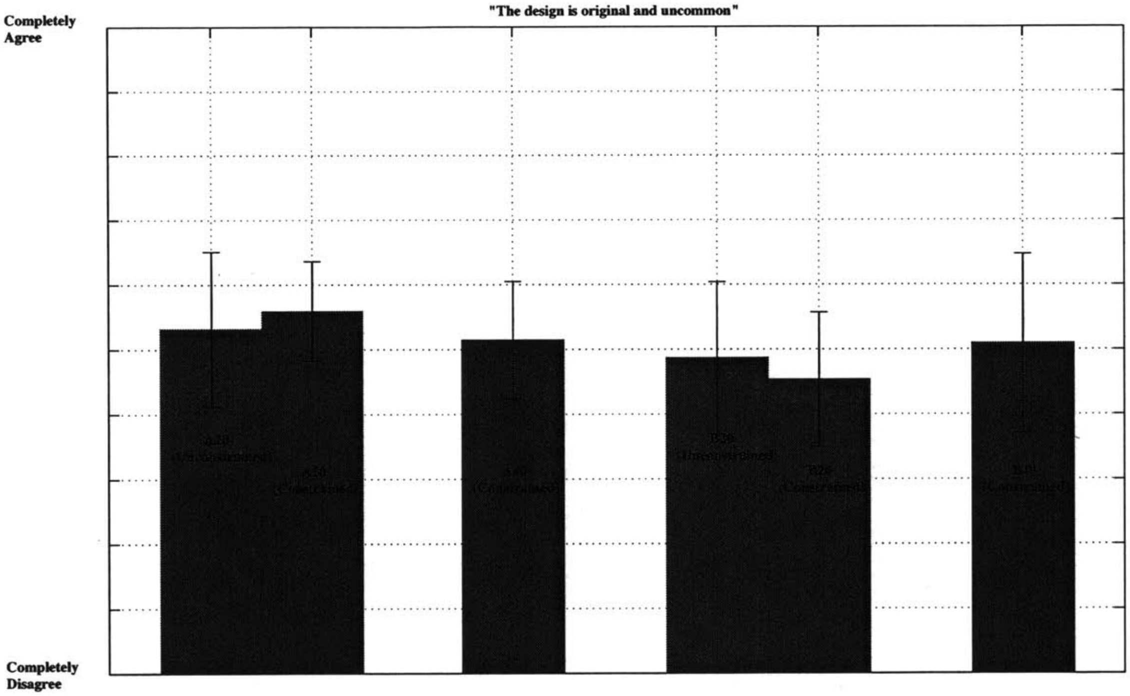


Figure 16. Campus A on average produced more novel concepts than Campus B. Being constrained later had a positive effect on novelty in Campus A and a negative effect on Campus B

Since these numbers are contradictory to the number of sketches generated per group, correlations between the quantity and sketch ratings were also analyzed but no strong correlations were found.

5.4.3.3 Comparing the Most Novel Design Created Per Participant

Since designers often ideate multiple ideas and then select one to pursue, in order to not penalize students who had some lower-scoring designs, the highest scoring design per participant was also considered. In this case a two-way ANOVA test looking at the most novel designs produced while participants were constrained revealed no significant differences. This is an interesting result, which suggests that the difference in prototyping environment or design strategy may not matter if only the most novel design is considered and not the average novelty of all designs generated.

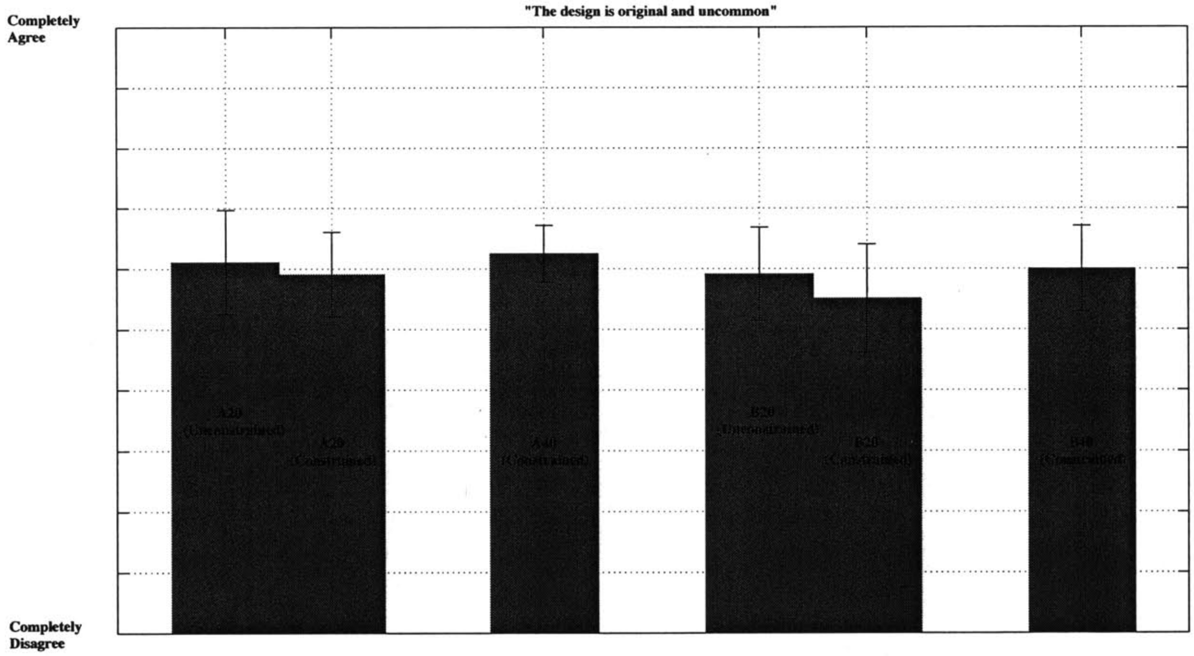


Figure 17. There is no significant difference in the novelty of the most novel design produced per participant

5.4.4 Appropriateness

5.4.4.1 Top 10 Most Appropriate Designs

For the appropriateness metric, evaluators were asked if the design addressed the needs of the user and would be applicable in the setting depicted in the design prompt. The top ten most appropriate designs were split relatively evenly among the experimental groups with 20% from A20, 10% from A40, 30% from B20, and 40% from B40. 70% were generated by Campus B.

An example of a design that scored highly on the appropriateness metric is a wheelchair with an electric elevator to lift the seat (Figure 18).

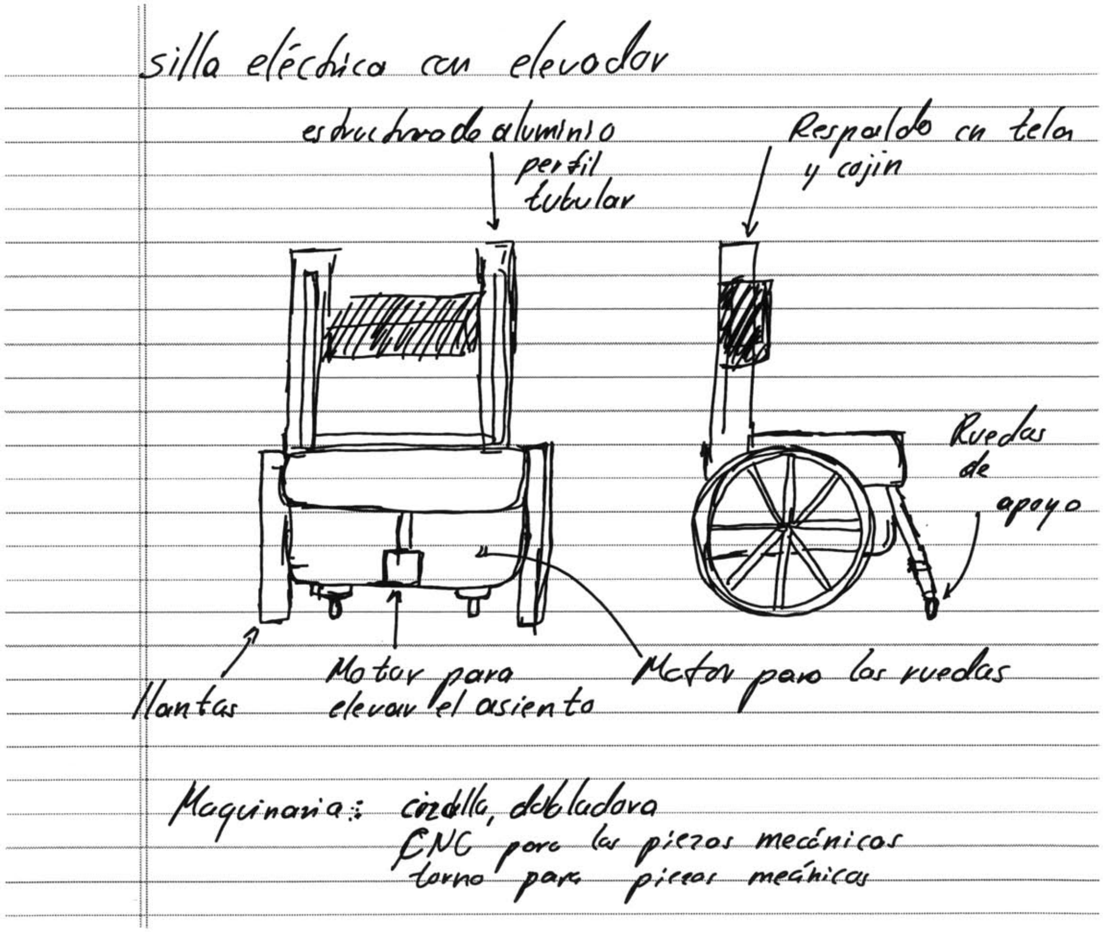
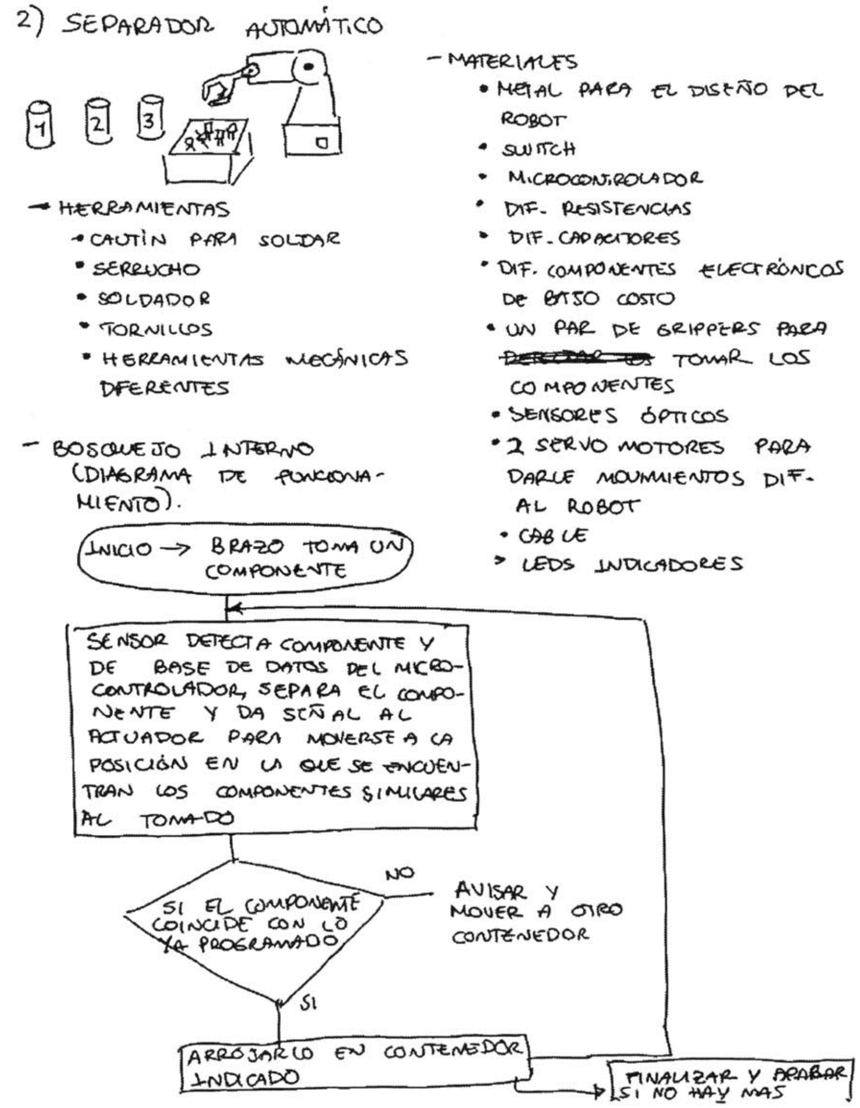


Figure 18. Electric wheelchair with lift

An example of a design that scored lower on the appropriateness metric is an electronic arm for separating components (Figure 19). Since the user in the prompt had limited mobility in his legs, this device does not clearly address his problem.


2) SEPARADOR AUTOMÁTICO

- HERRAMIENTAS
  - CAUTÍN PARA SOLDAR
  - SERRUCHO
  - SOLDADOR
  - TORNILLOS
  - HERRAMIENTAS MECÁNICAS DFERENTES

- MATERIALES
  - METAL PARA EL DISEÑO DEL ROBOT
  - SWITCH
  - MICROCONTROLADOR
  - DIF. RESISTENCIAS
  - DIF. CAPACITORES
  - DIF. COMPONENTES ELECTRÓNCOS DE BAJO COSTO
  - UN PAR DE GRIPPERS PARA ~~DETECTAR LOS~~ TOMAR LOS COMPONENTES
  - SENSORES ÓPTICOS
  - 2 SERVO MOTORES PARA DARLE MOVIMIENTOS DIF. AL ROBOT
  - CABLE
  - LEDS INDICADORES

- BOSQUEJO INTERNO (DIAGRAMA DE FUNCIONAMIENTO).

Figure 19. Component separator

5.4.4.2 Appropriateness of Designs Produced Per Group

An ANOVA analysis conducted on the appropriateness of the designs produced while participants were constrained revealed statistically significant interaction effects (p=0.0002). Campus A produced more appropriate designs when they were constrained halfway through while Campus B produced more appropriate designs when they were constrained at the beginning. This metric takes into account the average scores of all of the sketches in each group (Figure 20).

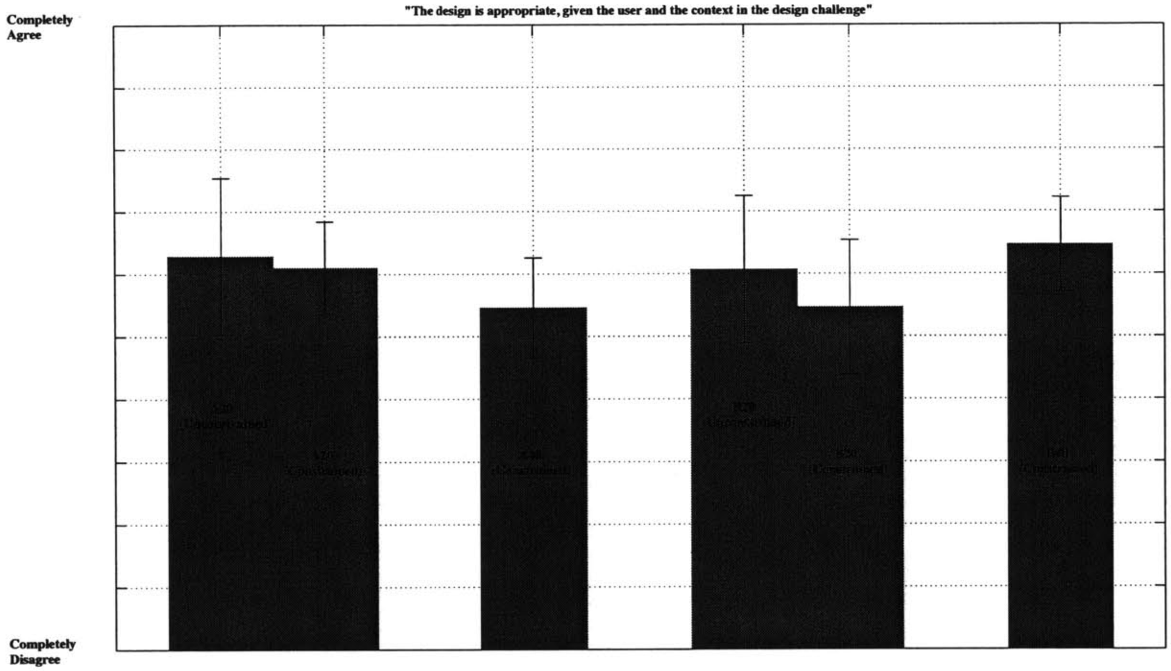


Figure 20. There were significant interaction effects for the impact of the experimental treatment on the appropriateness of concepts developed

The result of an interaction goes against hypothesis 2a that the timing alone would affect the appropriateness of concepts. Therefore the impact must be more complicated and nuanced. This difference in appropriateness could be explained by their starting point, or "frame of reference." Students in groups A20 and B40 tended to start with existing technologies in the spheres of both the design for disability and industrial spaces, and adapt them to resource and budget constraints. Participants in A40 tended to come up with more ideas that were less likely to be on the market, and therefore probably more difficult to judge if they would be appropriate to the user and context. Students in B20 also tended to focus on making very simple and low-cost devices even when they were not constrained by materials, which may have caused them to over constrain their design space early on, and therefore later propose solutions that were less appropriate to the design task.

5.4.4.3 Comparing the Most Appropriate Design Created Per Participant

Looking at only the highest scoring sketch per participant on the appropriateness metric, a two-way ANOVA analysis of the most appropriate designs produced while constrained revealed no statistically significant results (Figure 21). This result again suggests that while the experimental treatments could affect the average of ideas that are generated, it is possible to get the same result regardless of prototyping environment or design process. These differences could help support the idea that generating a lot of concepts before the selection phase could be even more important when environmental and timing effects could be impacting designers.

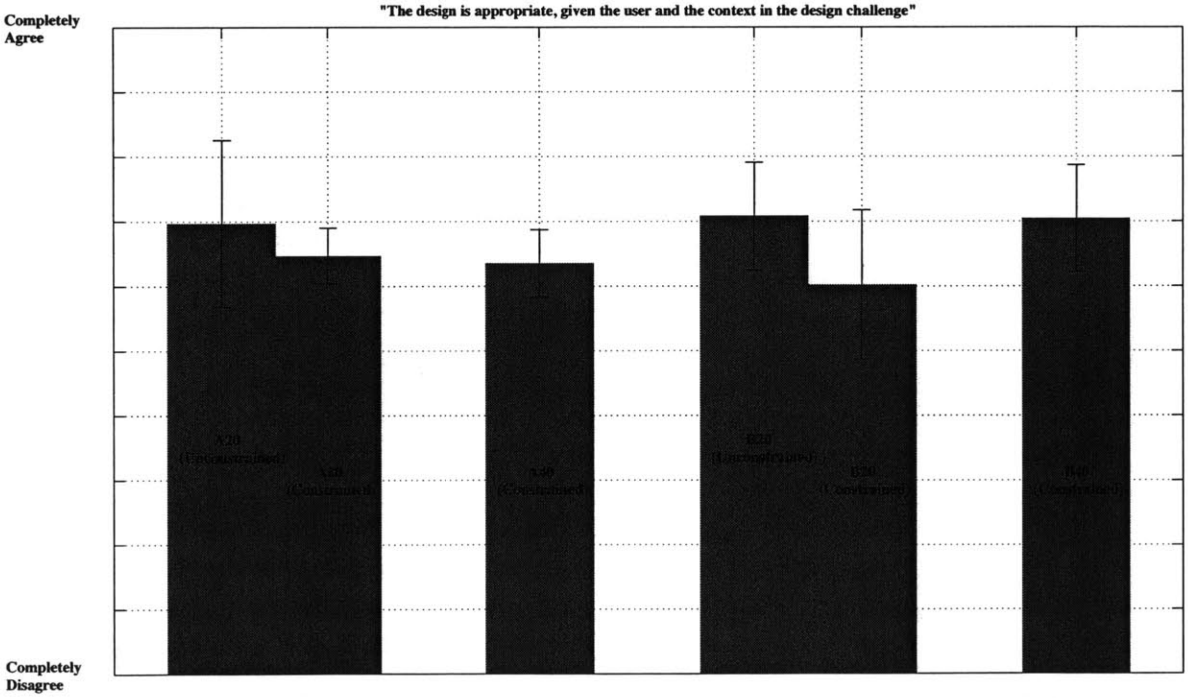


Figure 21. No significant impact of experimental treatments on the most appropriate design created per participant

5.4.5 Technical Feasibility

5.4.5.1 Top 10 Most Technically Feasible Designs

Evaluators were also asked to rate how technically feasible the designs were. Out of the top 10, 20% were from A20, 10% from A40, 40% from B20, and 30% from B40. 70% were from Campus B, which is consistent with hypothesis 3b.

An example of a design that scored highly on technical feasibility was a wheelchair ramp for a truck (Figure 22).

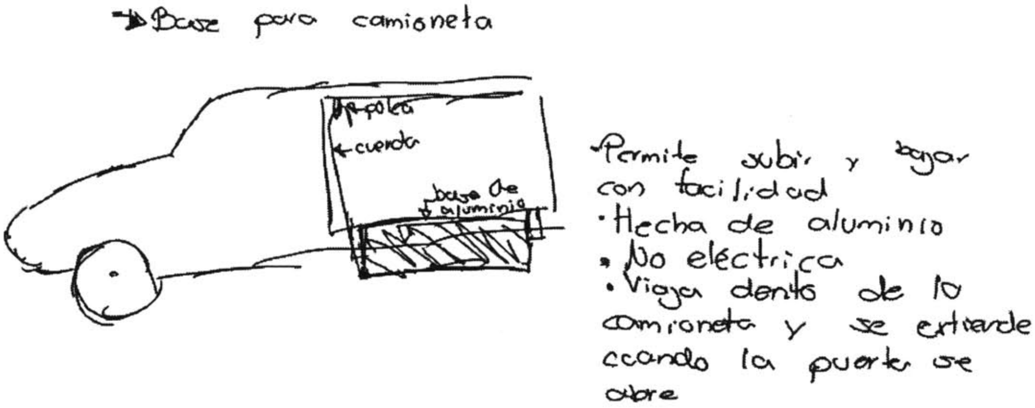


Figure 22. Wheelchair ramp for a truck

An example of a design that scored lower on technical feasibility was a device that claimed could use the force from a bike pump to lift objects and close doors (Figure 23).

Monta cajas

Material
Bomba de aire
PVC
Extrusión de aluminio (ángulo)
Resorte de compresión
Abrazaderas
Tornillos
Pegamento

Con la ayuda de una bomba de aire, utilizar la presión ejercida por esta en un tubo de aluminio conectados por una manguera, con el objetivo de que se mueva una barra de aluminio y de esta forma activar uno o varios mecanismos para por ejemplo levantar cajas cerrar puertas, etc.

Se ilustrara el mecanismo para levantar cajas

Mediante la presión del aire se podría levantar una barra y en su final se podrían colocar cajas o materiales similares.

Herramientas
Taladro
Tijeras
Segueta
~~Tornillos~~ Pinzas
~~Pegamento~~ Desarmador
~~[illegible]~~ Martillo

Figure 23. A device for lifting boxes

5.4.5.2 Technical Feasibility of Designs Produced Per Group

After an ANOVA analysis of the sketches produced while constrained, statistically significant interaction effects were found (p=0.0477). Campus B produced on average more technically feasible designs when they were constrained from the beginning, while Campus A produced more technically feasible designs when constrained halfway through (Figure 24). The difference however is more pronounced in Campus A. This could be related to the fact that students in other groups tended to reference other products and technologies, while group A40 generated more ideas based off of the given materials.

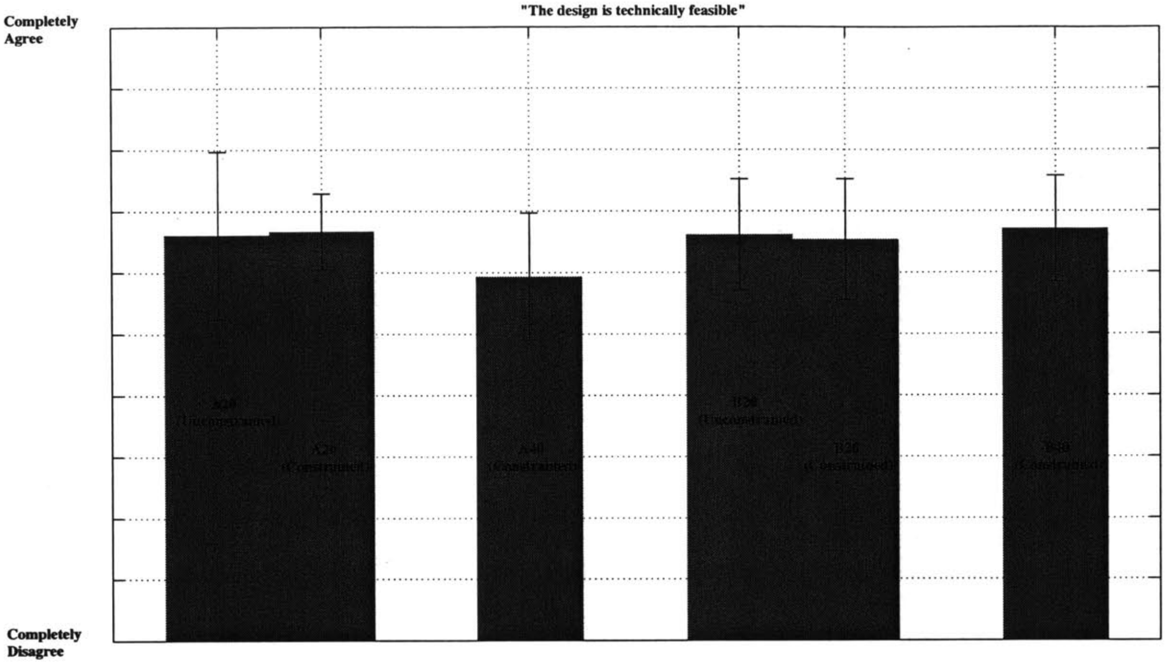


Figure 24. The average technical feasibility of designs by group A40 was slightly lower than in other experimental treatments

5.4.5.3 Comparing the Most Technically Feasible Design Created Per Participant

Looking at only the top scoring, the most technically feasible design generated per participant, a two-way ANOVA analysis revealed no statistically significant effects. Once again, this result suggests that while the design strategy and regular prototyping environment could have an effect on the body of ideas generated, they do not affect the possibility of obtaining similarly performing designs (Figure 25).

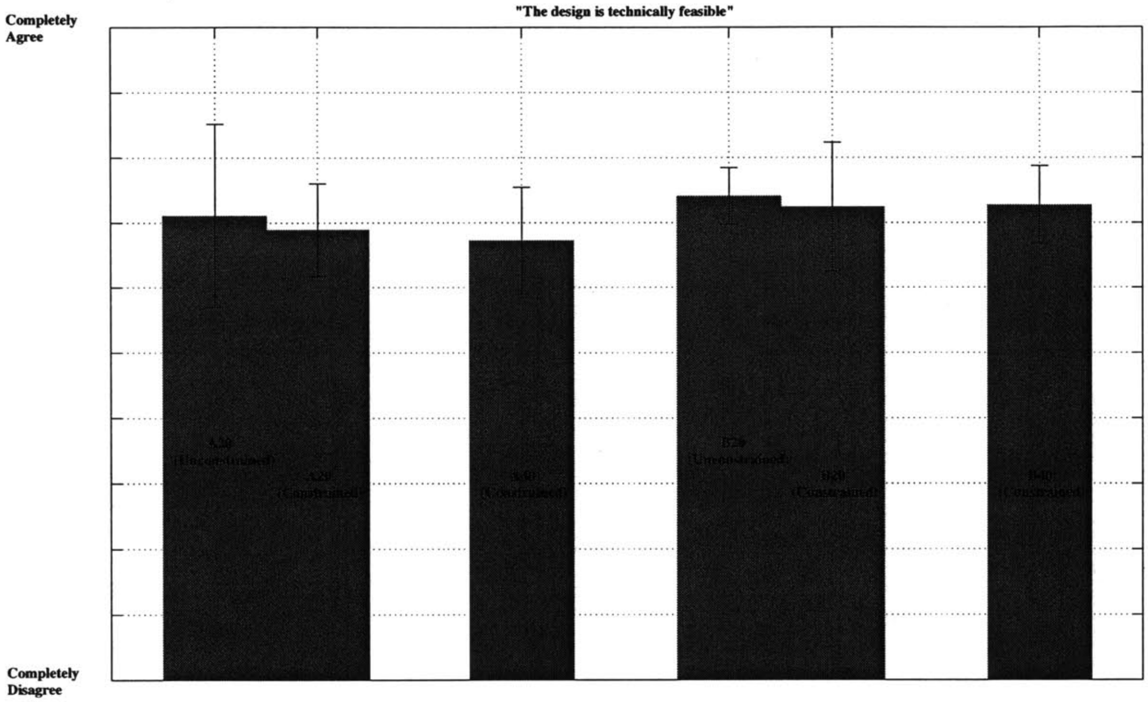


Figure 25. No significant effects of experimental treatment on the most technically feasible design produced per person

5.4.6 Marketability

5.4.6.1 Top 10 Most Marketable Designs

Evaluators were also asked to rank if they thought that the product could be commercialized. Out of the top ten designs, 20% were designed by A40, 30% by B20, and 50% by B40. 70% were designed by participants who were constrained from the beginning.

An example of a highly marketable product was the design for a shelving unit that spins to allow better access without requiring the user to move (Figure 26).

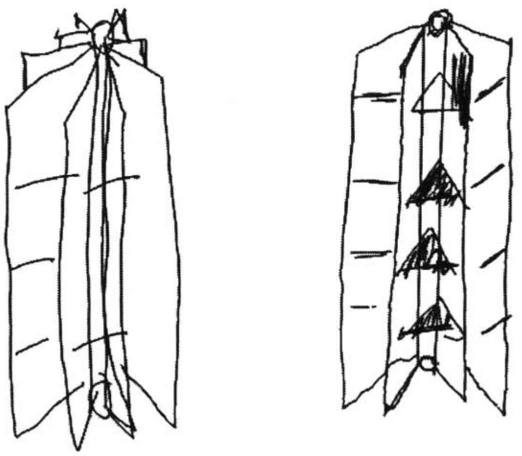


Figure 26. Rotating shelf

An example of a design that scored lower on the marketability metric is this large rail system that runs the length of the store to transport goods (Figure 27).

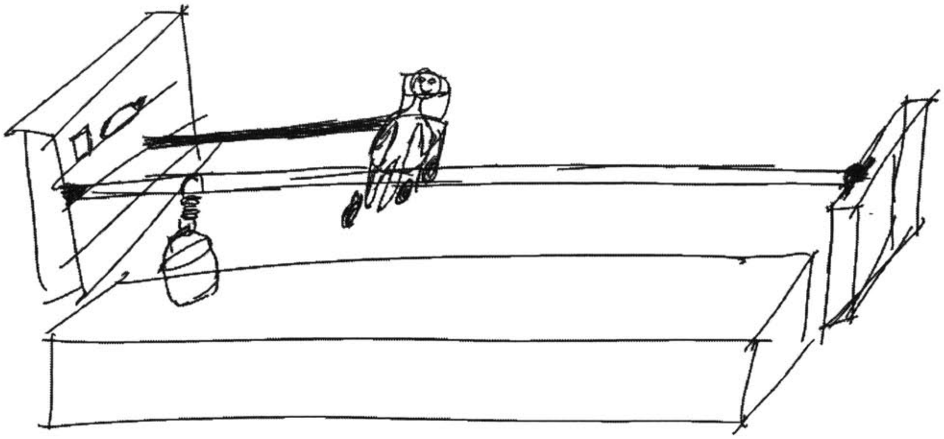


Figure 27. Rail installation for moving goods

5.4.6.2 Marketability of Designs Produced Per Group

After an ANOVA analysis of designs produced while constrained, statistically significant interaction effects were found (p=0.0098). Campus B produced on average more marketable products when constrained at the beginning, while Campus A produced more marketable designs on average when they were constrained halfway through (Figure 28). Similar to the appropriateness metric, this may be a reflection of the fact that it was easier for the Mechanical Turk evaluators to rate an idea that echoed an existing product as more marketable.

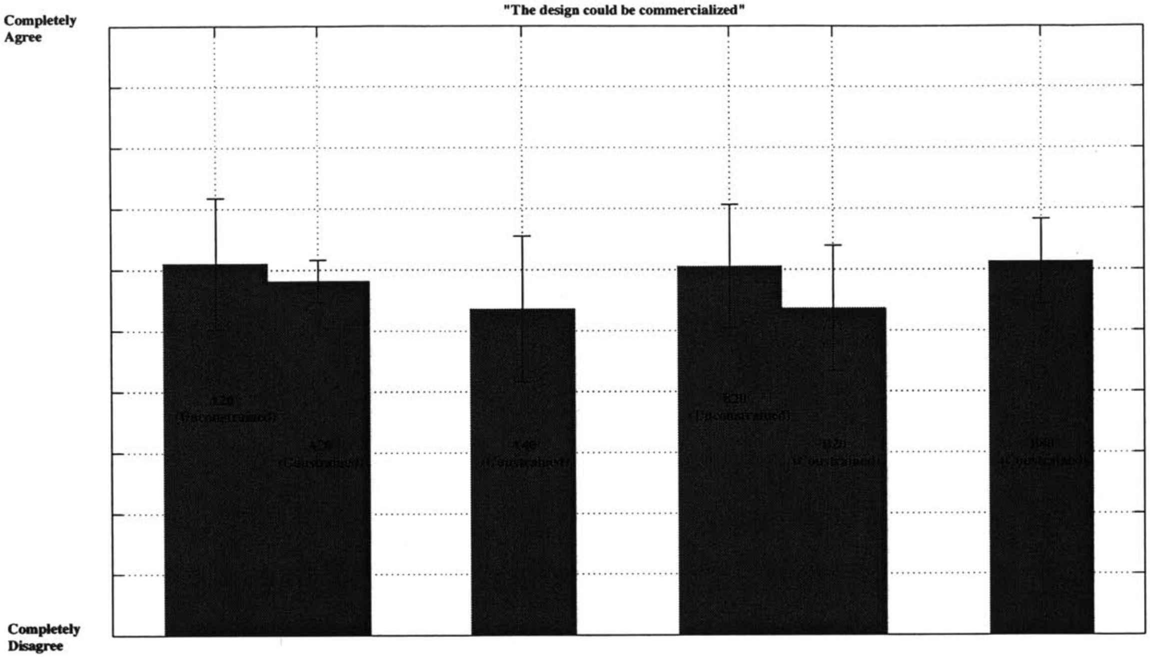


Figure 28. Significant interaction effects on the marketability of designs

5.4.6.3 Most Marketable Design Created Per Participant

Looking at the design per participant that received the highest marketability score, a two-way ANOVA analysis revealed significant experimental effects (p=0.0154), where the most marketable designs produced by the group that was constrained at the beginning were more marketable that the best produced by the group halfway through. This is against hypothesis 2b, which suggested that having fewer constraints at the beginning of the design process would allow designers to more easily reference existing and therefore marketable solutions. While the sample size is too small to be conclusive or generalizable, this result does question the theory that constraining designers later on is always better for idea generation. It is also important to notice that while all groups came up with similarly marketable ideas during the experiment, the group that was constrained at the beginning were more successful at "overcoming" the constraints, while the group that was constrained halfway through saw a drop in the marketability of their concepts. It may be that following a 3D concurrent engineering strategy allowed students to better balance the multiple competing requirements of user needs, manufacturing, and supply chains in order to create a product that would be successful in the target market.

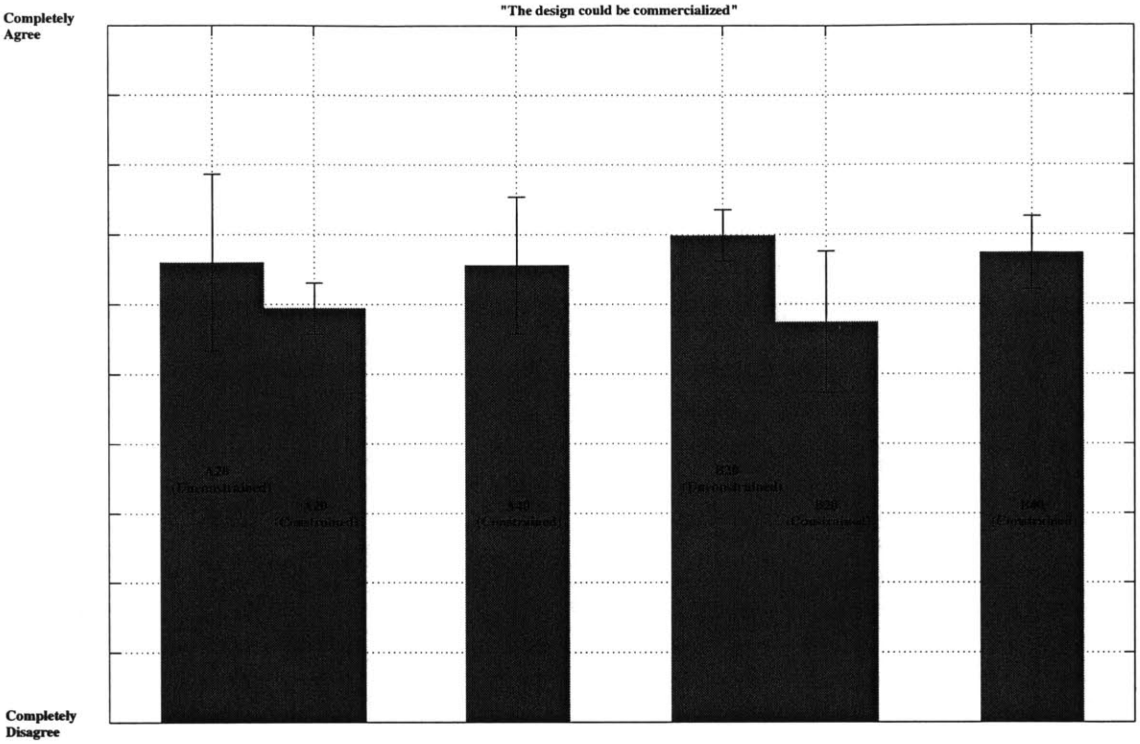
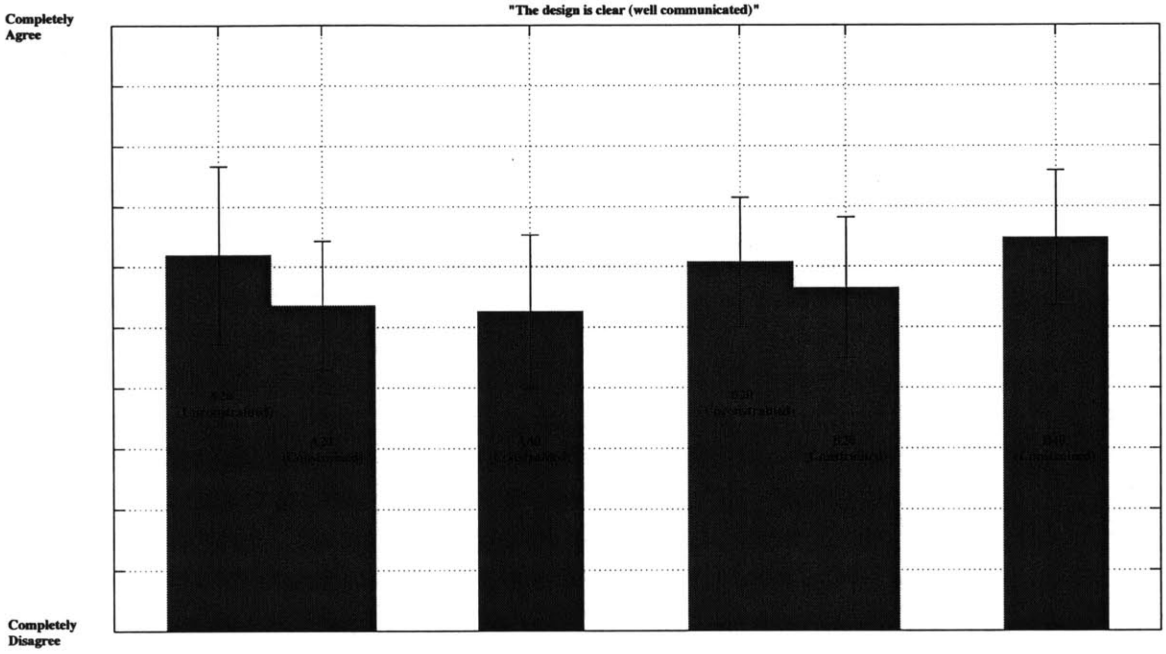


Figure 29. Significant experimental effects in the marketability of the most marketable design produced per participant. The group that received information about prototyping material constraints at the beginning of the exercise tended to have a most marketable idea that scored higher than the group that was constrained halfway through.

5.4.7 Clarity

After an ANOVA analysis of all of the designs produced while participants were constrained, statistically significant campus effects were found (p=0.0103), with Campus B producing on average more clear sketches. However, no strong correlations were found between clarity of the sketches and the other metrics.



5.4.8 Multi-variable Analysis

5.4.8.1 All Designs per Group

Many design studies look not only at novelty and appropriateness as separate metrics, but are interested in the combination, as most successful designs will be both new and useful. An ANOVA test based on the combined novelty and appropriateness scores of each sketch produced while the participants were constrained again revealed significant interaction effects (p=0.0002). Campus A produced more novel and appropriate sketches when they were constrained halfway through while Campus B produced more novel and appropriate designs when they were constrained at the beginning (Figure 30).

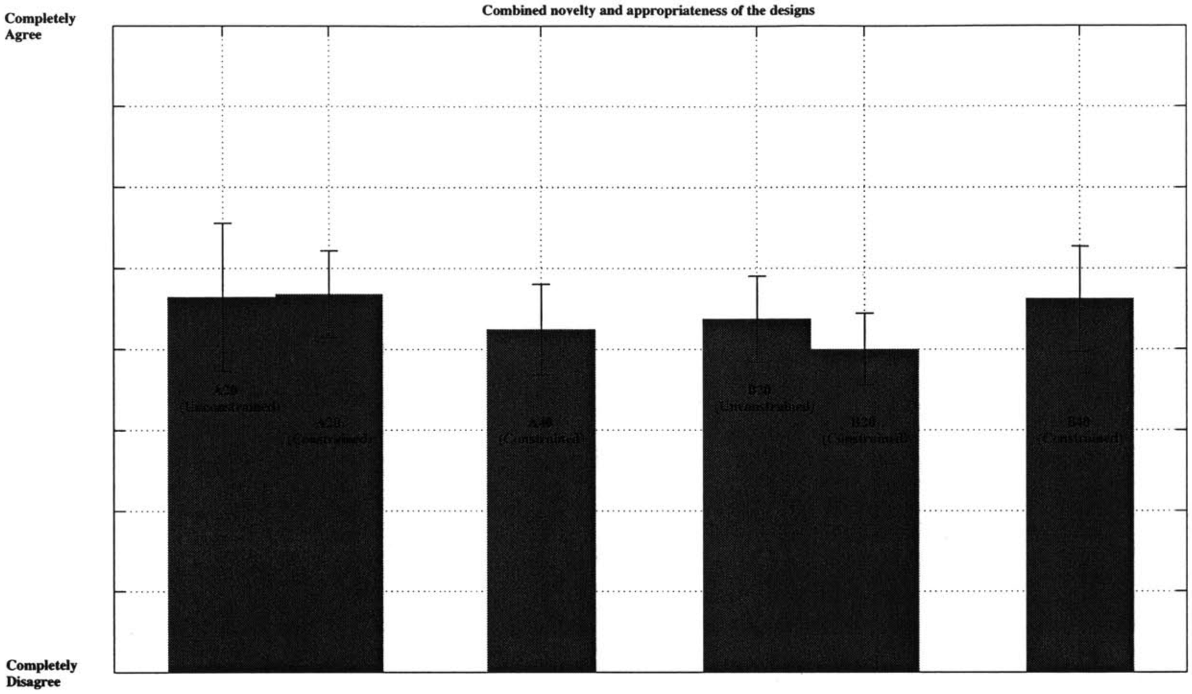
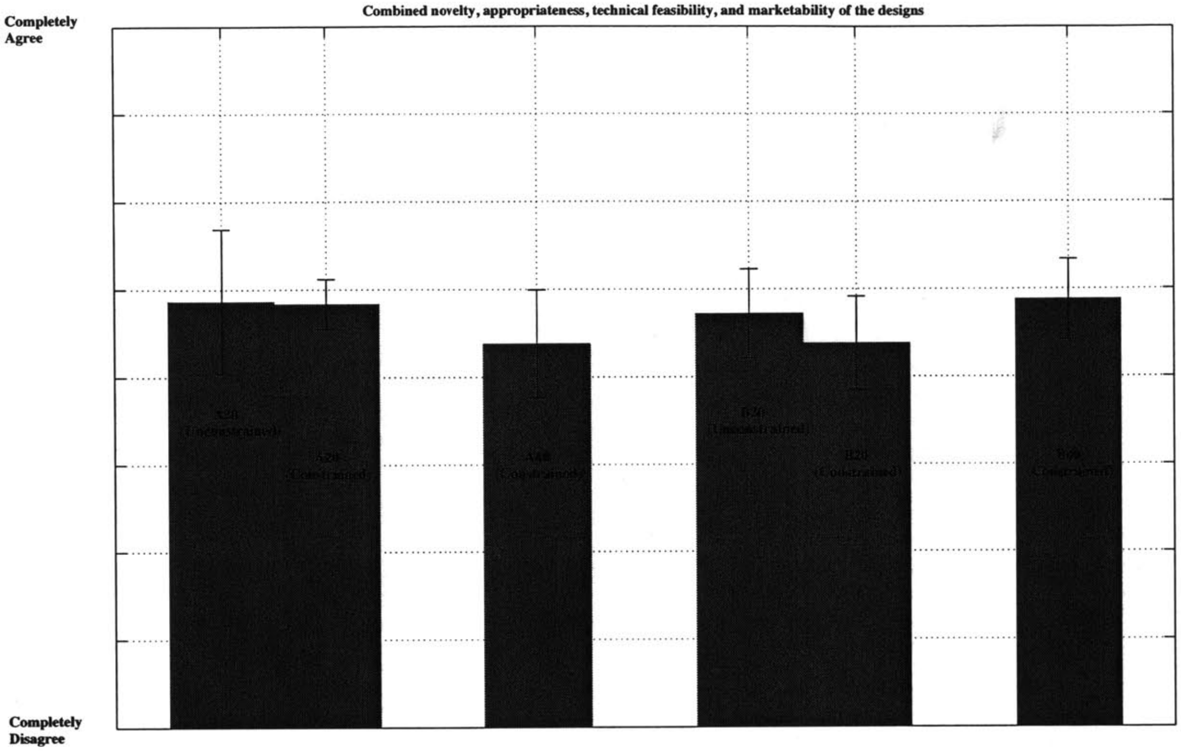


Figure 30. Significant interaction effects for combined novelty and appropriateness of all designs produced

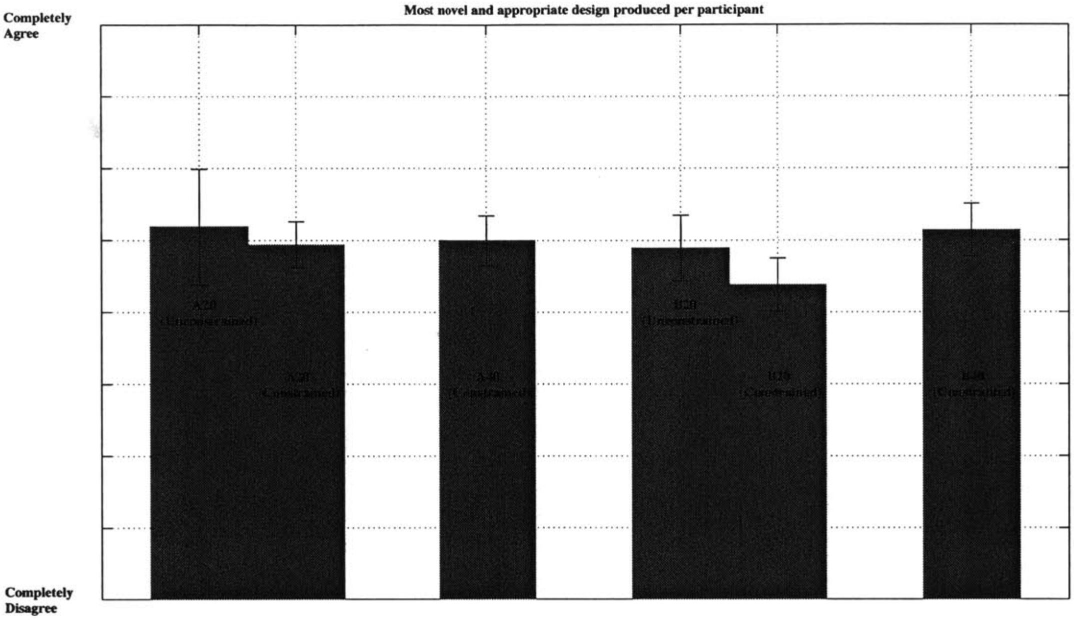
There were also significant interaction effects for Novelty and Technical Feasibility (p=0.0035), Novelty and Marketability (p=0.0016), Appropriateness and Technical Feasibility (p=0.002), Appropriateness and Marketability (p=0.0006), Technical Feasibility and Marketability (p=0.0136) and Novelty, Appropriateness, Technical Feasibility, and Marketability combined (p=0.0003). All of the interaction effects are skewed in the same way, with Campus A performing better when they were constrained halfway through, and Campus B performing better when constrained at the beginning.



5.4.8.2 *Best Designs Created Per Participant*

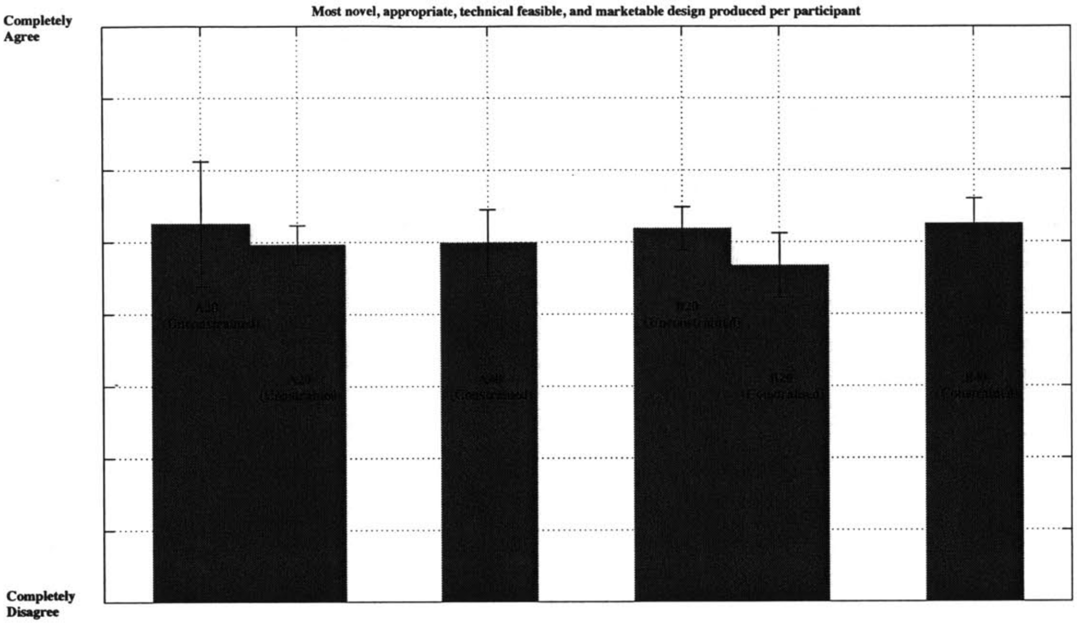
While looking at the sketches that received the highest score in a single metric did not reveal many significant effects, comparing how participants scored over multiple dimensions at once revealed interesting results.

Looking at designs that scored highest in novelty *and* appropriateness revealed significant experimental (p=0.0072) and interaction (p=0.0201) effects. Participants that were constrained at the beginning generally produced more novel and appropriate designs than participants who were constrained halfway through, but the largest difference was within Campus B.



Looking at novelty *and* marketability also revealed significant experimental effects (p=0.0108).

An ANOVA test of all four metrics combined (novelty, appropriateness, technical feasibility, and marketability) did not reveal significant effects, *however,* t-tests within the campuses revealed an insignificant difference between the experimental groups in Campus A, but a significant difference in Campus B (p=0.0195). The same occurred when examining novelty and appropriateness (p=0.0023), novelty and technical feasibility(p=0.0125), and novelty and marketability (p=0.0099). Only marketability has this effect on its own (p=0.0404). The other results are combination effects.



These results are extremely interesting because they suggest not only that practicing a variety of design processes and strategies can better prepare students to be more flexible, but that certain strategies could be more beneficial, depending on the dominant design processes of the designers and the desired outputs.

5.5 General Discussion

The prevalence of the interaction effects could be explained by the difference in the prototyping environment and the regular design strategies of the students. Students in Campus B are more accustomed to designing a product and selecting materials and components that will solve the problem as simply and elegantly as possible, which was evident in the concepts generated when the B20 group was unconstrained. However, once their prototyping environment was changed and the constraints were introduced, they may have had more difficulty incorporating this new information into their design process, and their concepts ended up scoring lower on the metrics, as compared to their peers who were given the constraints at the beginning. This result may be due to fixation on earlier design solutions and previous approaches for designing products out of raw materials. They tried to reference past experiences but then many of the students became too fixated and had more difficulty adapting. This result has been mirrored in countless anecdotes of engineering students who are used to designing in one setting and then run into difficulties when they cannot implement the path of least resistance in a new setting, and have to “make it work.”

The relative higher scores of the B40 group compared to the B20 group when they were constrained could be explained by the different frames of reference that were encouraged by the different timing of introducing the constraints. The B40 group may have had an easier time adapting to the constraints because the materials were incorporated into their “design world’ from the beginning, before they had time to become fixated on a particular design or process and were more open to unexpected combinations. Therefore, B40 may have been performed better because they accepted the provided materials as part of their design space, rather than over-constraining themselves too soon. From the comments by students, the material constraints seemed to help “ground” them by providing specific materials to ideate off of. This is consistent with studies that have shown the impact of visual stimuli for inspiration (Goldschmidt & Smolkov, 2006; López-Mesa, Mulet, Vidal, & Thompson, 2011).

Interestingly, the opposite effect occurred in Campus A, where the group that followed a divergent to convergent process (A20) scored relatively higher on the metrics than their peers in the group that was constrained from the beginning (A40). This could be explained by the earlier revelation from the interviews that students in Campus A tended to follow a variety of design processes and often needed to be flexible and adaptable in their past design projects. Therefore, while the students in A40 were designing within a design space and frame of reference provided by the list of materials, the students in group A20 were first able to reference any available technology and material, and then they later used that inspiration to create adaptations that would be feasible given the materials constraints. The combination of the shift in frame of reference that the two-part design strategy allows, along with the students’ greater flexibility allowed them to expand their design space further, which resulted in higher scoring concepts.

The students’ complex reaction to this experiment is reflective of the literature on entrepreneurship. Successful, adaptable businesses seem to depend on a combination of both physical and financial resources and the “entrepreneurial capacity” of employees to question the status quo, reengineer existing products and systems, and exploit available resources (Newbert, Gopalakrishnan, & Kirchhoff, 2008). Preparing product designers for rapidly changing environments may also depend on creating systems that help foster and support adaptive innovation (Bransford, 2007).

5.6 Limitations of the Study

Given that this investigation was structured as a case study, there are limitations in the generalizability of the results. However, the goal of this investigation was to study the components and linkages of a system in order to apply a conceptual framework to multiple case studies that can be reproduced and modified to extract more detail in future studies. Case studies are ideal for researching phenomenon within its real-world context when the boundaries between the phenomenon and the context are not clearly evident (Yin, 2009).

However, given the complex nature of these topics, especially how a designer's context influences their design process, there is always an opportunity to create a more robust study by collecting more data, over a longer time frame. Since this study was based on the accounts of students about past projects and their performance during a sketching exercise, it may not accurately depict their actual design process. However, this is a common limitation of many design research studies and the general insights are still interesting to stakeholders, even if the specifics could be modified.

A rival explanation for why certain design strategies could occur could be because of personal problem solving style or the differences between prototyping with electronics and mechanical components. It could also depend on the type of project, as previous design studies have shown that the nature of the task itself can have an effect on design. For this reason, interviews with a number of students were conducted in order to understand if the effect in general swings the student population one way or another, and tried to capture as many details as possible about their past prototyping experiences to give context to their answers. However, more details and a study with a larger student population would help to balance these effects.

Another problem with this type of analysis is that people often do not remember why they made certain decisions in the past, as much of design can be unconscious. It is also possible that students interpreted the open-ended questions differently. Further long-term studies will need to be conducted to understand the causal mechanisms more in depth during the product development cycle, but this study aims to provide a theoretical framework supported with anecdotal evidence to suggest that this is a rich area for investigation.

5.7 Summary

While the sample size was small and therefore this study is not generalizable to design everywhere, the data obtained from this group of students yields some interesting results and invites further investigation. As hypothesized, the campus that was used to being more resourceful produced more novel concepts and it was also found that they were less affected by changes in timing of when constraints were introduced. An unexpected and interesting finding was that interaction effects were found with the majority of the metrics, most of which suggesting that being constrained early on produced better outcomes in a campus where students were used to following a divergent to convergent process. This could be due to a frame of reference, where students who are used to having fewer restrictions become more adept at honing in on a potential solution early on, and since they do not need to be adaptable, have a harder time adapting to changes in the solution space. By giving these students a more restricted world, they can more easily push to the boundaries of that solution space.

On the other hand, for students who are used to being adaptable, they seem to produce better outcomes when they are given freedom to reference outside technologies, and then adapt those ideas to work with the constrained resources. The results of this experiment seem to suggest that better design outcomes result from a combination of being able to reference as large a solution space as possible, while also being as flexible as possible. This suggests that engineering design curriculum and innovation policy should not only focus on improving access to resources and information, but also encourage flexible and adaptable engineers.

6. Implications for Engineers and Innovation System Designers

6.1 Overview of the Chapter

In the first chapters of this thesis, a conceptual model was introduced that linked product designers and engineers to system designers and policymakers. This model was supplemented with relevant theory from the existing literature, and the data collected through a series of multiple embedded case studies. This chapter will revisit the model, addressing measures that all stakeholders can take in order to improve outcomes in their innovation system, including design strategies and policy recommendations (Figure 31).

Figure 31. Policies and design strategies are mechanisms for affecting change in an innovation ecosystem

6.2 Design Strategies

The results of this study suggest that having a variety of design experiences that require different design processes could help designers become more flexible and adaptable. Hentschel describes three mental blocks that prevent unorthodox use and "new context imagination," functional fixedness, conforming behavior, and automatic response (Hentschel, 2011). These are all responses that are engrained by culture and habit. The results suggest that the change in design process did not have as significant an effect on designers used to working in a more constrained setting. Therefore in order to expand their toolkit of design strategies and to prepare them for unknown situations, engineers should actively take on projects in a variety of prototyping environments and cultures.

It also suggests that the timing of constraints can affect how students approach a design challenge, and that the impact of the timing could depend on the student's dominant problem solving strategy. Therefore, understanding the engineer's dominant design process, and encouraging students to complete design projects with a variety of ideation processes could lead to better outcomes, depending on the nature of the design challenge. Even in settings where resources cannot be augmented or changed, studies have shown that teaching design methods have had an impact on invention (Girón, Hernández, & Castañeda, 2004).

If the prototyping or design culture is cost conscious or encourages re-use and sustainability, than these principals can be taken into account early in the design stage of the initial prototype. Rather than creating throwaway prototypes, designers can leave room for future changes given feedback by using a modular instead of an integral design, and designing the prototype for disassembly.

Strategies include principles from design for disassembly, recycling, repair, and upgrading, such as these strategies outlined by Autodesk (Autodesk, 2011):

- Use standard-size modular parts
- Use standard cross-platform connections
- Design easy access to parts that are likely to become obsolete or need to change
- Avoid paints, additives, and surface treatments
- Avoid combinations of materials that are difficult to separate
- Use modular assemblies that enable the replacement of discrete components
- Design connections that are visually and physically accessible
- Require only a few standard tools
- Use human-scale fasteners and use hand-strength press-fits instead of tight press-fits
- Avoid glues, and use only glues that are easily soluble or heat reversible.
- Include parts list and part numbers in technical documentation

At the end of the exit questionnaire, students were asked if and how they thought that their experience during the design exercise would affect how they approach design projects in the future. This question was meant to capture their main takeaway from the experience. Most of the comments were on the benefit of having more practice designing solutions to an open-ended, user-centered challenge. Many mentioned that this type of exercise allowed them to reflect on their strengths and weaknesses.

Others mentioned that they would want to know the materials and tools available for prototyping in early stages of design (67% of participants in the A-20 group, 33% of the A-40 group, 29% of the B-20 group, and 71% of the B-40 group). Interestingly these results mirror the ratings of design outcomes by objective evaluators. If the students who were more consciously concerned about balancing multiple constraints and objectives achieved better design outcomes in the end, this could provide more evidence in support of 3D concurrent engineering during the design process.

6.3 Policies

Policymakers can also play a significant role in both creating and manipulating the system and the prototyping resource environment. Specifically there are two buckets of polices, at the university or firm level and the public policy level.

There have been many articles on whether having constraints or not leads to better design outcomes. The dominant policy strategy however is to support more resources, less barriers and higher design budgets as long as there is enough money. However, this system design may be suboptimal because it can decrease the adaptability of designers. A stronger policy would incorporate a laboratory design and design curriculum that encourages both exposing students to the world of available technologies, while requiring students to consider resource constraints, to expand their design options, and force them to aim for high technical performance, meeting user requirements, while minimizing cost and environmental impact. Essentially, since prototyping resource environments are variable, varying the range of design challenges will help students to become more adaptable to new situations, and allow them to practice different design strategies to increase their design options.

Incorporating constraints into engineering curriculum in more affluent areas is one strategy for improving design outcomes, but not all areas have the same resources. There are many settings where prototyping resources are limited, greater investment is not immediately feasible, and waste is a large concern.

Therefore, while investment in more machines, a larger inventory, and reducing budget constraints for designers can be the best strategy in some cases depending on the design goals, these measures are not always feasible. In this case better information management and design tools could be useful to help students make as many design decisions as possible before committing physical resources.

Most students interviewed mentioned that they tended to sketch ideas and create CAD models before committing to building a prototype, however CAD was not always useful for modeling their particular design issues, especially when working with found objects with complicated geometries rather than parts that were machined from scratch. A wider library of components found locally could help improve the design capability while reducing costs. Better linkages between designers and local hardware stores and suppliers, to link information not only about product availability and price, but dimensions, materials, and stock to a centrally located hub such as an app, would allow designers to more easily take available components into consideration during the idea generation phase, without requiring them to travel to multiple locations or re-work the design once a component was either not found, or if the discovery of component sparked a better design idea. As 80% of a designer's time can go to information management task such as searching for components, low-cost tools that can help with this process during the idea generation stages could be beneficial (Will, 1991).

Other potential policies include:

- Financial assistance to update equipment in public centers of higher education
- Leasing equipment or licensing deals with industry
- Concentrating resources in "innovation centers."
- Revise trade policies to ensure lower-cost components for new designs
- Provide support to help local suppliers upgrade their capabilities
- Improve communication channels to help match the needs of distributed inventors to local and international suppliers
- Incorporating design and prototyping into the national innovation strategy can help reduce obstacles to innovation and ensure that policies are addressing the needs of designers

For policymakers looking to develop an ecosystem of innovation, whether at a firm, university, country or international level, this research suggests that is it important to take into account material supply chains and capital goods used in early-stage design. University educators should be especially aware of the impact available materials and tools have on the design process and problem solving. Therefore, to help promote innovation, one should be conscious not necessarily of the amount of tools or materials available, but if they address the needs of inventors, and if diversifying the supply chains can help promote more novel design outcomes.

6.4 Summary

By investigating an innovation ecosystem and product design through the lens of prototyping resource environments, it is possible to not only better understand the system, but to isolate opportunities for improvement. From encouraging students to practice designing in multiple contexts, to incorporating design for sustainability strategies in the prototyping stage, it is possible to foster more adaptable engineers who can produce designs with a smaller environmental and economic footprint regardless of where they find themselves in the future. Policymakers and system designers can also improve the outcomes of their university, firm, state, or country by being conscious of the prototyping needs of local designers and enacting policies to enhance either access to tools or to education about alternative design strategies.

7. Conclusions

7.1 Key takeaways

The major messages of this thesis were:

- Prototyping resource environments vary, around the world and within a country or state
- Optimal strategies for one context could be suboptimal in others
- Design experience in multiple types of environments could improve adaptability
- This conceptual framework can help stakeholders to analyze and improve the design of innovation systems by examining them through the lens of early-stage design and prototyping resource environments

Referring back to the research questions, data from this research project has supported most of them, but there are more complicated interaction effects involved, which suggests that the influence of the timing of resource constraints could depend on the designer's usual prototyping environment.

Research Question #1

How does the prototyping resource environment that students learn in influence their design decisions and processes?

Hypothesis #1a

Students in more resource-constrained settings will have had more experiences adapting their designs to resource constraints. **True**

Hypothesis #1b

"Thinking inside the box" and abstraction of the design before searching for materials will be more common in resource-constrained environments. **True**

Research Question #2

Assuming a constrained prototyping resource environment, how does the timing of information about the constraints influence early-stage design outcomes?

Hypothesis #2a

Knowing constraints earlier on will result in more appropriate concepts for the user. **Slightly true, but also depends on the designer's home prototyping environment.**

Hypothesis #2b

Knowing constraints later will result in more marketable designs. **False. Knowing constraints earlier on tended to result in more marketable designs.**

Hypothesis #2c

Knowing constraints earlier will result in more novel designs. **True, but the designer's home prototyping environment also had an effect.**

Research Question #3

Does the prototyping resource environment that students learn in influence their design outcomes when they are put into a more constrained environment?

Hypothesis #3a

Students with more practice working with constraints will develop more novel concepts. **True.**

Hypothesis #3b

Students with more resources will develop more technically feasible concepts. **True, but the timing of constraints could also play a role.**

7.2 Opportunities for Further Studies

These case studies answered some questions while opening up many new possibilities for further research. For example, many participants remarked that it would have been interesting to work on this design challenge in a team. A team challenge was rejected for the purpose of this experiment because the goal was to understand how resources affected individual students and because team dynamics could have added their own effects. However a team challenge would have many useful applications for product development and could be an interesting area to explore. Analyzing team discussions may lead to more insights on the thought process that occurs when solving these types of problems. It would also be a good replication of product design in firms, which are often carried out in teams.

The design challenge was structured so that students would need to think about all aspects of the design, from the user interface to material selection and manufacturing, to encourage a holistic approach to design. One student commented that he would have liked to know which aspect of the design to focus on. Given that the engineers and designers in most large companies are divided into specific specialties, it may be interesting to see how these restrictions influence design choices when they are given to a specific type of professional versus when one person is designing the whole system. If a team of designers is solving this design challenge, it may be interesting to assign each team member a specific perspective of designer, manufacturer, or purchaser and then observe how these viewpoints were combined into the final product.

It may also be interesting to see if there is a difference in how novices and professional designers react to this experiment, because while it is possible that experts may be more used to incorporating multiple criteria into their idea generation, they could also be more fixed in their past experiences and therefore less adaptable.

7.3 Applications in Other Settings

This study could be replicated in any country, but Mexico was chosen because the author had previous experience in the region and because there are a wide range of prototyping environments throughout the country, from high-tech labs in industry and academia, to rural communities. The results could be interesting for designers in high-resource settings who are interested in expanding their arsenal of design techniques, for engineers who want to work on design projects in less resource-rich settings, and for engineering universities and inventors in low-resource settings. Researchers may also want to apply this research design to other settings both within Mexico and in other countries.

These findings are relevant to university settings, as well as firms that develop and manufacture products, or individual inventors. By swapping the available materials and the design prompt, this study could be applicable to any project that requires innovative designs for a new product, with limited supply chains or on-hand prototyping materials to test and communicate the design ideas. The study is also relatable for small industrial producers, where individuals are often required to fulfill both production and organization functions, as compared to more specialized roles in larger firms (Bhalla, 1989).

7.4 Summary and Concluding Thoughts

There are clear advantages of learning from building. Research studies have communicated the importance of feedback from prototyping, and the Mexican students interviewed for this study often talked about how much they had learned from designing and building devices in the research lab. Technology capacity policy focuses on improving investment in tools, and the theory from the leading design firms in the U.S. emphasize play, throwaway prototypes and frequent experimentation. Encouraging greater "technology capacity" i.e. more technology around the world is one strategy that has been shown to be effective.

However, being forced to learn how to design with severe constraints is an important design skill that needs to be cultivated in order to foster engineers and designers that are confident in creating innovative designs when resources are limited. As resource constraints become an increasingly important issue in design, the future will call for successful, flexible engineers who can not only design and manufacture "ideal" products, but who are equally able to apply their analytical and creative skills to improving and reworking existing products, structures, and systems. Valuing one paradigm or process over another restricts the number of possibilities, and breakthrough innovation is possible when both ideologies are combined, as the growing number of success stories from emerging markets have shown.

Figure 32. The choice does not have to be either/or, and encouraging both design and policy strategies of higher investment and resourcefulness can result in a larger possible design space for solving problems

There is acknowledgement of the need for more culturally aware and flexible engineers who are prepared to work internationally (Downey & Lucena, 2005). There is also more pressure now for innovative solutions that go beyond engineering status quo to use scarce resources in new ways. At the same time, there are hundreds of emerging and developing countries that want to expand their economies, develop and export products, and provide essential goods and services to their populations who do not have access to the same wealth as developed countries.

In order to encourage R&D, prototyping, and innovation in any setting, regardless of whether policies are constructed at a firm or countrywide level, it is important to be conscious of supply chains. As this study shows, the resources available for prototyping influence not only the design outcomes, but also the process that engineers follow. Just as firms are conscious of the manufacturing supply chains and public policymakers are concerned about creating an infrastructure for innovation, they should also be concerned about how the supply chains are affecting early-stage design.

The broad goals of the study were (1) to draw attention to the impact of the prototyping environment on students' experience and development as engineers and (2) to encourage an open, cross-cultural discussion of whether design processes are "one size fits all." A framework for approaching design and engineering analysis when prototyping with limited finances and physical resources would not only help engineering students in low-resource settings learn and create products, but it would provide students in higher-resource settings with techniques to become more adaptable and creative designers. Solving global issues such as poverty, food and water shortages, and healthcare is going to require the joint efforts of engineers and inventors throughout the world. By examining the design process and adapting it to different conditions, we can foster individuals who are prepared to design in any environment, with any level of resources, and increase global capacity to engineer solutions to society's toughest problems.

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9. Appendices

9.1 Procedure

A. Tell them about the study, give them the consent forms to sign

> "*You will participate in a design experiment for 40 minutes then an interview. There is nothing dangerous about this study but I need to have you sign a consent form.*"

B. Give them the entry questionnaire
C. *Have them do a warm-up exercise (1 minute)*
D. Then give them the first page of instructions to read
E. Show them the Livescribe notebook and pen, explain what it's for

> "*You will use this pen and paper to sketch. This will allow us to have a digital copy of what you are writing.*"

F. Allow them to read the rest of the prompt, remind them they have 40 minutes to complete the exercise. Start timing when they look like they have already read the instructions, asked any questions and look ready to begin.
G. Remind them how much time is left every 10 minutes
H. After 20 minutes, give the two part group the materials and the second part of the prompt
I. Encourage them to keep brainstorming for the full 40 minutes. At the end allow them to finish up their last thought
J. Ask them to pick their top 2 designs
K. Ask them to explain their designs
    a. *What does it do? How does it work? How did you come up with it?*
    b. *Why did you pick those two as your favorites and not the others?*
    c. See if you can get them to talk about their thought process.
L. Give them the exit questionnaire to fill out, collect other materials, review answers to entry questionnaire to use as prompts for interview
M. Give them chocolate and the interview consent form
N. Commence interview, starting from asking about their previous prototypes

9.2 Experimental Group #1 (Generate ideas for 20 minutes then work under constraints for another 20 minutes)~ English Translation

Design Background

Undergraduate

1. University (and campus if applicable): ______________________________
2. Semesters completed: ______________
3. Major: ______________________________________
4. If you have/had a focus within that major such as electronics, programming, biology, etc. please specify it here: ___________________________

Post graduate (if applicable)

5. Master's semesters: _____ university/campus: ________________________________

focus: ____

6. Doctorate years: _______ university/campus: ________________________________

focus: ____

7. Industry years: _______ location: _______________________________________

industry: ____

8. Please list any previous experience designing and building prototypes including design courses, internships, or personal projects:

Project name	class/lab/job/personal project	Personal Role in the Project
ex: Hydro-powered lantern	*class (group project)*	*product design, fabrication of casing*

Turn over ➡

Think back to your previous experiences designing and building prototypes when answering the following questions. ***Please circle one for each category:***

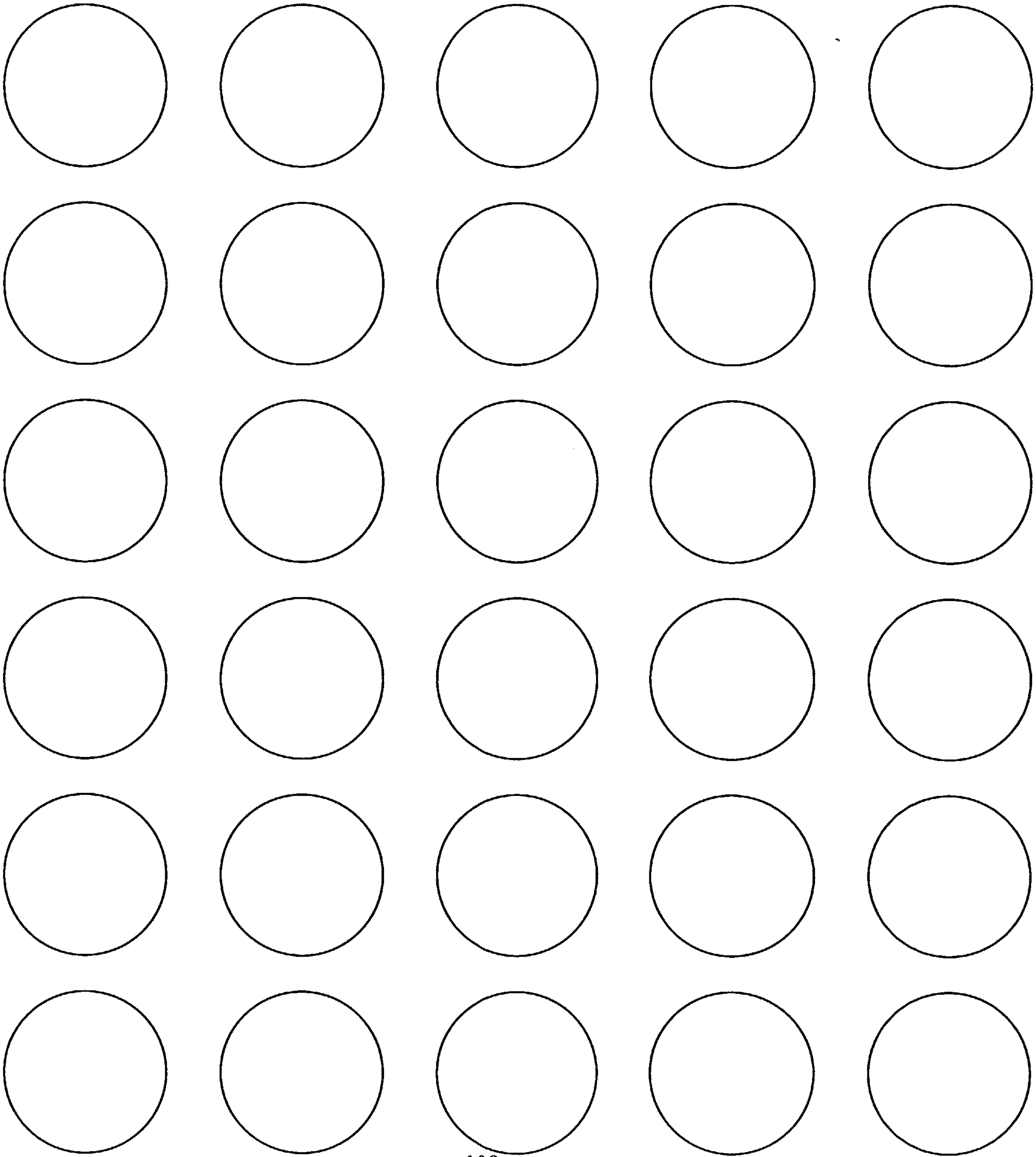
9. When creating prototypes, did the following factors influence your design process?

	No, not at all	**Yes, very little**		**Yes, moderately**			**Yes, a lot**
a) peer review feedback	1	2	3	4	5	6	7
b) instructor or supervisor feedback	1	2	3	4	5	6	7
c) user feedback	1	2	3	4	5	6	7
d) access to prototyping tools							
i) hand tools	1	2	3	4	5	6	7
ii) machine shop tools	1	2	3	4	5	6	7
e) personal manufacturing/ machining ability	1	2	3	4	5	6	7
f) material availability							
i) basic electronic components	1	2	3	4	5	6	7
ii) advanced electronics	1	2	3	4	5	6	7
iii) raw materials	1	2	3	4	5	6	7
iv) mechanisms	1	2	3	4	5	6	7
g) prototype assembly	1	2	3	4	5	6	7
h) budget	1	2	3	4	5	6	7
i) the business plan	1	2	3	4	5	6	7
j) aesthetics	1	2	3	4	5	6	7
k) time constraints	1	2	3	4	5	6	7
l) time required to procure materials	1	2	3	4	5	6	7
l) other: ____________	1	2	3	4	5	6	7

10. If you have any comments or thoughts about the questions or would like to give a more detailed explanation to any of your answers, please use the space below.

Warm-up Exercise

You have one minute to draw as many pictures as you can, using the circles below.



Idea Generation Exercise

Orientation to the Company

You are an engineer working for a small firm that designs affordable, high-quality products for use by small businesses. Your boss has asked the engineering team to come up with ideas for new and innovative products that will be marketed to a specific population. He is requesting that you provide a sketch and brief plan for manufacturing a prototype of each idea.

Your boss will judge the designs given the **creativity** of the product, how well it fits into the target **user context** and the **feasibility of constructing a prototype** given the detail in your sketches. The products should be mainly mechanical, but may use some electrical components. The prototypes should be robust enough to be tested by users in the field.

A description of the target context and a typical customer were compiled by the marketing team, and will be available for reference.

Deliverables

Try to come up with **as many ideas** as you can. Please sketch every idea on a separate sheet of paper; include a title for the sketch, clearly show the mechanisms, and note the materials and tools required to build a physical prototype of your design. Detailed descriptions of programming and electrical circuit design are not necessary. Exact measurements and full sentences are also not required.

You are free to use as much paper as you need. You will have approximately 40 minutes to sketch. At the end of the brainstorming session you will be asked to explain your ideas.

Stop

Please wait for further instructions.

Design Project

As of 2000, there were approximately 800,000 people in Latin America and the Caribbean with permanent or temporary disabilities due to diabetes. In Mexico the figure was 178,785 people, resulting in an indirect cost of around $12.4 billion.[1]

Your firm is interested in designs for new and innovative products that will aid physically disabled shopkeepers, to help recently disabled people continue to work and provide for their family. Existing products on the market are either too expensive or do not address the specific needs of shopkeepers. As a reminder, your boss is looking for designs that are **creative, fit into the user context, and can be feasibly built.**

Checklist of Deliverables

As a reminder, try to come up with **as many ideas** as you can. You are free to sketch and use as much paper as you like but for each **complete design** you should have at a **minimum**:

☐ a title

☐ at least one detailed sketch that clearly shows the mechanisms

☐ materials you would use for each part

☐ tools you would use to construct the prototype

---

[1] Barceló, A., Aedo, C., Rajpathak, S., & Robles, S. (2003) The cost of diabetes in Latin America and the Caribbean. *Bulletin of the World Health Organization,* 81(1), 19-27.

Note From Your Boss

Materials and Tools

Your boss has just informed you that prototyping resources are limited so from now on assume you are restricted to designs that could be built using materials included in the attached list. For early-stage prototyping, the firm has access to a variety of hand tools but no advanced tools such as lathes, milling machines, injection molding or 3D printers. You can assume you have access to fasteners and basic electronics (such as nuts/bolts, screws, adhesives, solder, wire, etc.).

You have 20 more minutes to sketch ideas.

Reflections

1. How difficult or easy did you find the design task?

	very difficult						**very easy**
1st half	1	2	3	4	5	6	7
2nd half	1	2	3	4	5	6	7

2. How satisfied are you with your designs?

	very dissatisfied						**very satisfied**
1st half	1	2	3	4	5	6	7
2nd half	1	2	3	4	5	6	7

3. How did you feel during the design activity?

	very frustrated						**very calm**
1st half	1	2	3	4	5	6	7
2nd half	1	2	3	4	5	6	7

4. Generally, how confident are you in your ability to design mechanical systems?

not confident at all						**very confident**
1	2	3	4	5	6	7

5. Generally, how confident are you in your ability to use shop tools?

not confident at all						**very confident**
1	2	3	4	5	6	7

6. How confident did you feel during this exercise?

	not confident at all						**very confident**
1st half	1	2	3	4	5	6	7
2nd half	1	2	3	4	5	6	7

7. Generally, how creative do you consider yourself?

not creative at all						**very creative**
1	2	3	4	5	6	7

Turn over ➡

8. How creative do you feel today?

	not creative at all						**very creative**
1st half	1	2	3	4	5	6	7
2nd half	1	2	3	4	5	6	7

9. Did you like the theme of the design prompt? (design for people with disabilities)

not at all						**a lot**
1	2	3	4	5	6	7

10. Did you feel that you had enough time to complete the design activity?

not nearly enough time			**just the right amount**			**too much time**
1	2	3	4	5	6	7

11. If you would like to expand on any of your previous answers, please use the space below.

12. Do you feel that this experience will affect how you approach future design projects? How?

13. Please include any other comments or suggestions about the design activity or this study here. We appreciate your feedback.

Thank you for participating!

9.3 Experimental Group #2 (40 minutes to generate ideas under constraints) ~ English Translation

Design Background

Undergraduate

5. University (and campus if applicable): ________________________________

6. Semesters completed: ______________

7. Major: ____

8. If you have/had a focus within that major such as electronics, programming, biology, etc. please specify it here: ____________________________

Post graduate (if applicable)

5. Master's semesters: _____ university/campus: _________________________________

focus: ____

6. Doctorate years: _______ university/campus: _________________________________

focus: ____

7. Work years: _______ location: ____

type of industry: ____

8. Please list any previous experience designing and building prototypes including design courses, jobs, or personal projects:

Project name	class/lab/job/personal project	Your Role in the Project
ex: Hydro-powered lantern	*class (group project)*	*product design, fabrication of casing*

Turn over ➡

Think back to your previous experiences designing and building prototypes when answering the following questions. ***Please circle one for each category:***

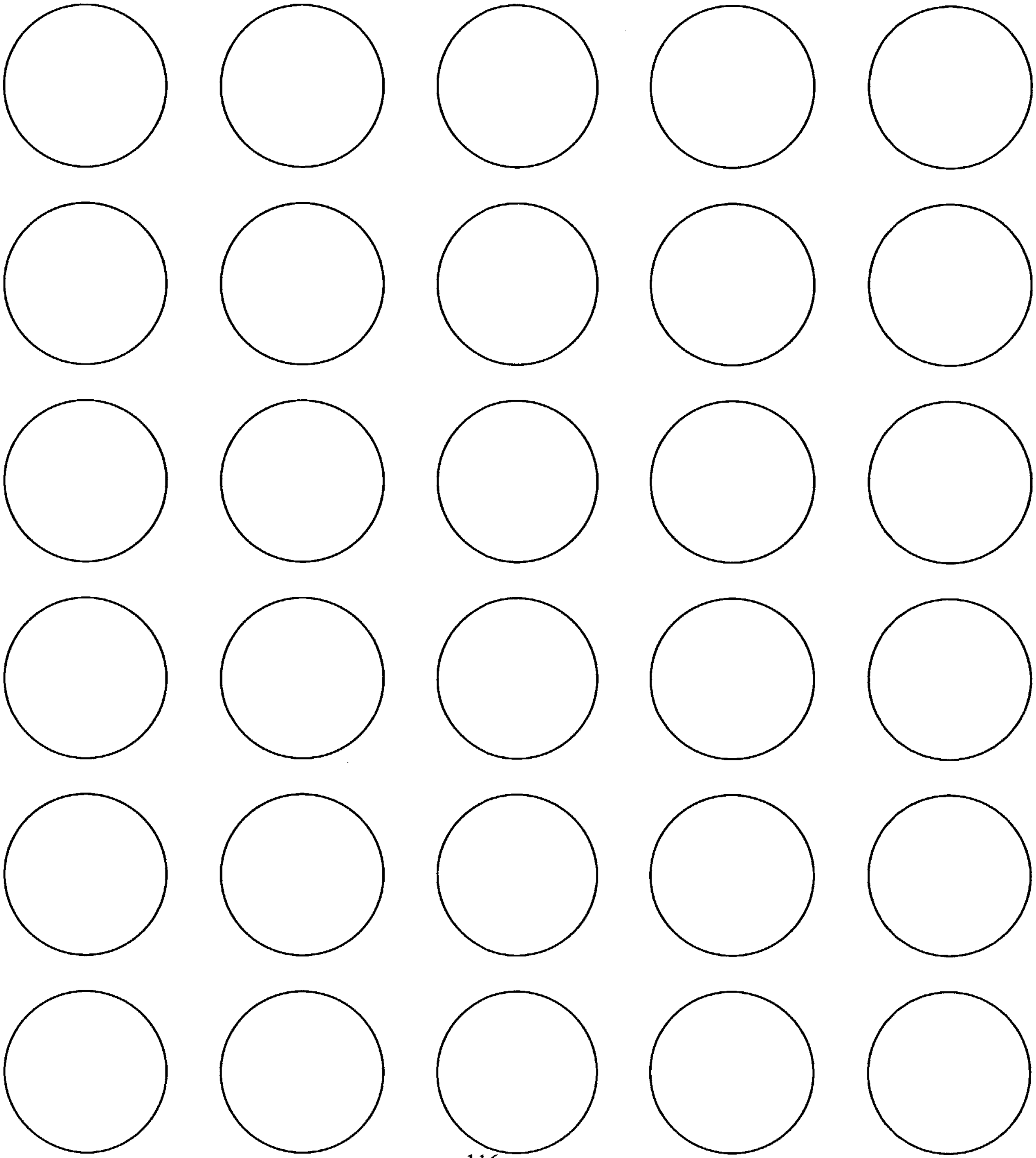
9. When you were creating prototypes, did the following factors influence your design process?

	No, not at all	**Yes, very little**		**Yes, moderately**			**Yes, a lot**
a) peer review feedback	1	2	3	4	5	6	7
b) instructor or supervisor feedback	1	2	3	4	5	6	7
c) user feedback	1	2	3	4	5	6	7
d) available prototyping tools							
i) hand tools	1	2	3	4	5	6	7
ii) machine shop tools	1	2	3	4	5	6	7
e) personal manufacturing/ machining ability	1	2	3	4	5	6	7
f) available materials							
i) basic electronic components	1	2	3	4	5	6	7
ii) advanced electronics	1	2	3	4	5	6	7
iii) raw materials	1	2	3	4	5	6	7
iv) mechanisms	1	2	3	4	5	6	7
g) prototype assembly	1	2	3	4	5	6	7
h) budget	1	2	3	4	5	6	7
i) the business plan	1	2	3	4	5	6	7
j) aesthetics	1	2	3	4	5	6	7
k) project deadline	1	2	3	4	5	6	7
l) time required to procure materials	1	2	3	4	5	6	7
l) other: ____________	1	2	3	4	5	6	7

10. If you have any comments or thoughts about the questions or would like to give a more detailed explanation to any of your answers, please use the space below.

Warm-up Exercise

You have one minute to draw as many pictures as you can, using the circles below.



Idea Generation Exercise

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Your boss will judge the designs taking into account the **creativity** of the product, how well it fits into the target **user context** and the **feasibility of constructing a prototype** given the detail in your sketches. The products should be mainly mechanical, but may have some electrical components. The prototypes should be robust enough to be tested by users in the field.

Descriptions of the target context and a typical customer were compiled by the marketing team, and will be available for reference.

Deliverables

Try to come up with **as many ideas** as you can. Please sketch every idea on a separate sheet of paper; include a title for the sketch, clearly show the mechanisms, and note the materials and tools required to build a physical prototype of your design. Detailed descriptions of programming and electrical circuit design are not necessary. Exact measurements and full sentences are also not required.

You are free to use as much paper as you need. You will have approximately 40 minutes to brainstorm and sketch. At the end of the brainstorming session you will be asked to orally explain your ideas.

Stop

Please wait for further instructions.

Design Project

According to a WHO publication from 2000, in Latin America and the Caribbean there were approximately 800,000 people who were permanently or temporarily disabled due to diabetes. In Mexico, the total was 178,785, resulting in an indirect cost of around $12.4 billion.[2]

Your company is interested in designs for new and innovative products that will aid physically disabled shopkeepers, to help recently disabled people continue to work and provide for their families. Existing products on the market are either too expensive or do not address the specific needs of shopkeepers. As a reminder, your boss is looking for designs that are creative, fit into the user context, and can be feasibly built.

Materials and Tools

Prototyping resources are limited so assume you are restricted to designs that could be built using materials included in the attached list. For early-stage prototyping, the firm has access to a variety of hand tools but no advanced tools such as lathes, milling machines, injection molding or 3D printers. You can assume you have access to fasteners and basic electronics (such as nuts/bolts, screws, adhesives, solder, wire, etc.).

Checklist of Deliverables

As a reminder, try to come up with **as many ideas** as you can. You are free to sketch and use as much paper as you need but for each **complete design** you should have at a **minimum**:

☐ a title

☐ at least one detailed sketch that clearly shows the mechanisms

☐ materials you would use for each part

☐ tools you would use to construct the prototype

---

[2] Barceló, A., Aedo, C., Rajpathak, S., & Robles, S. (2003) The cost of diabetes in Latin America and the Caribbean. *Bulletin of the World Health Organization,* 81(1), 19-27.

Reflections

1. How difficult did you find the design task?

very difficult						**very easy**
1	2	3	4	5	6	7

2. How satisfied are you with your designs?

very dissatisfied						**very satisfied**
1	2	3	4	5	6	7

3. How did you feel during the design activity?

very frustrated						**very calm**
1	2	3	4	5	6	7

4. Generally, how confident are you in your ability to design mechanical systems?

very unconfident						**very confident**
1	2	3	4	5	6	7

5. Generally, how confident are you in your ability to use shop tools?

very unconfident						**very confident**
1	2	3	4	5	6	7

6. How confident did you feel during this exercise?

very unconfident						**very confident**
1	2	3	4	5	6	7

7. Generally, how creative do you consider yourself?

not creative at all						**very creative**
1	2	3	4	5	6	7

Turn over →

8. How creative did you feel during this design exercise?

not creative at all						**very creative**
1	2	3	4	5	6	7

9. Did you like the theme of the design prompt? (design for people with disabilities)

not at all			**moderately**			**a lot**
1	2	3	4	5	6	7

10. Did you feel that you had enough time to complete the design activity?

not nearly enough time			**just the right amount**			**too much time**
1	2	3	4	5	6	7

11. If you would like to expand on any of your previous answers, please use the space below.

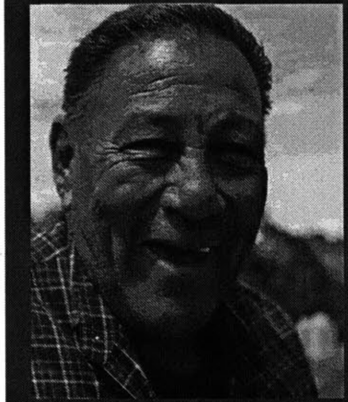
12. Do you feel that this experience will affect how you approach future design projects? How?

13. Please include any other comments or suggestions about the design activity or this study here. I appreciate your feedback.

Thank you for participating!

9.4 User Profile ~ English Translation

Typical User



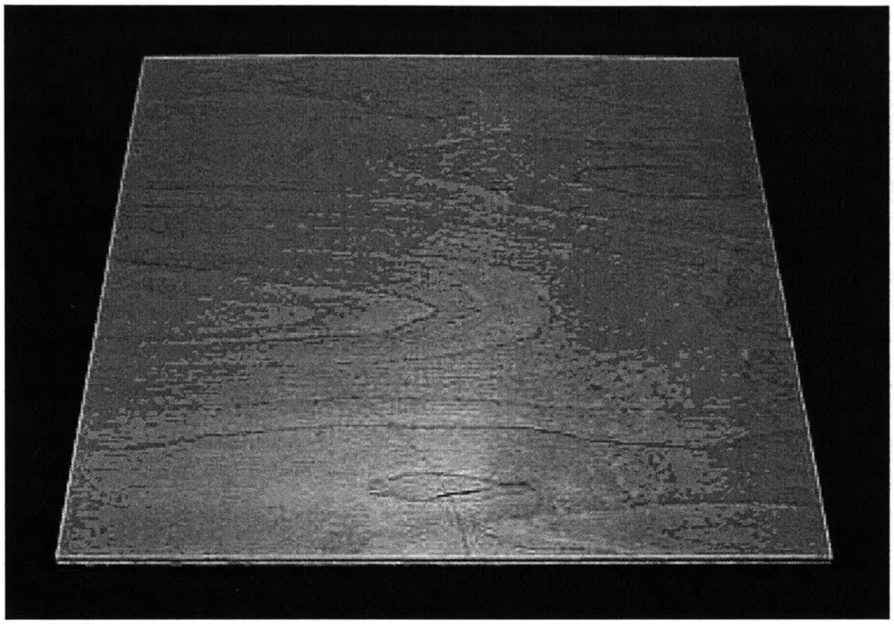
Name	Juan Alejandro Pérez González
Age	52
Location	Mexico City, Mexico
Occupation	Shopkeeper
Monthly Income	$380.00
Disabilities	Limited mobility in the legs

General Information

Juan has limited mobility in his legs due to untreated diabetes and is having a hard time working in the shop. Unfortunately, he can't afford any of the expensive tools currently on the market that could help him overcome his disability.

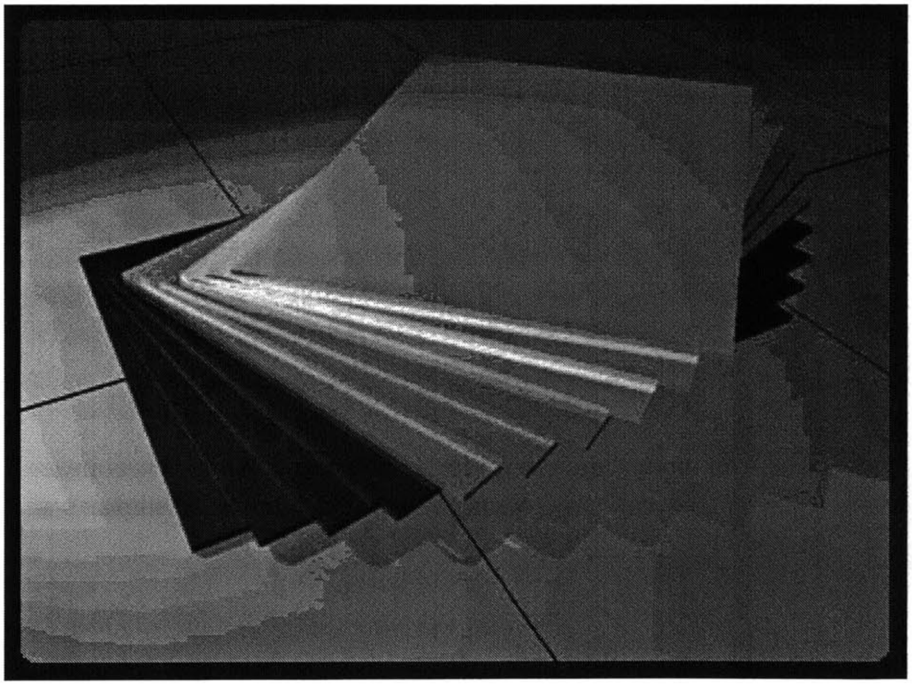
Examples of Shops

9.5 Materials List ~ English Translation



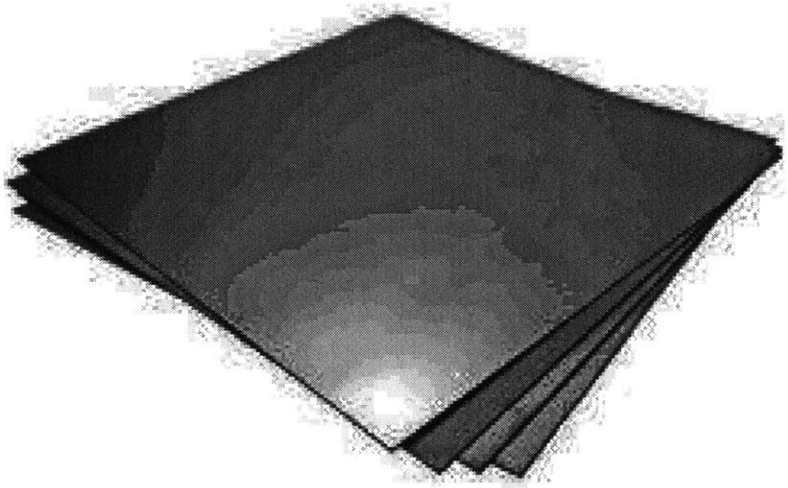
Plywood

thickness: 1/2"



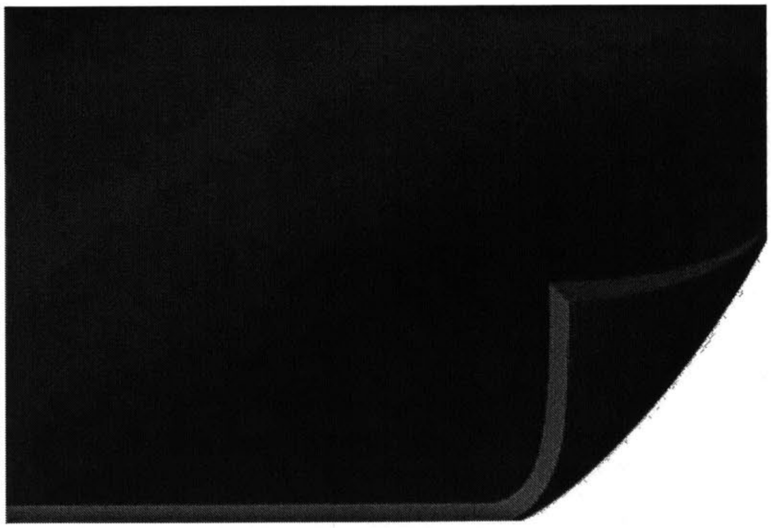
Plastic

thickness: 1/4"



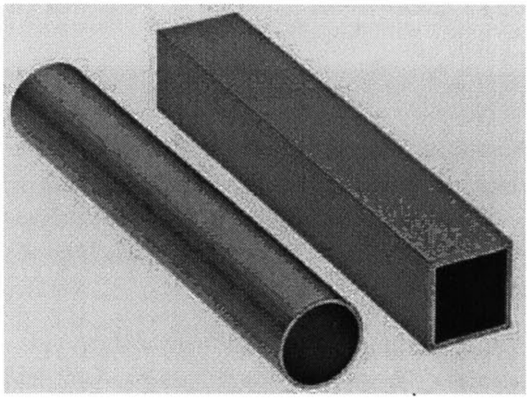
Aluminum/Steel Sheet

thickness: 1/16”



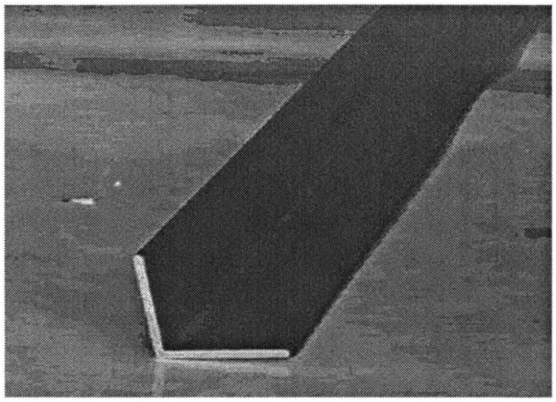
Rubber Sheet

thickness: 1/4”



Aluminum Extrusion

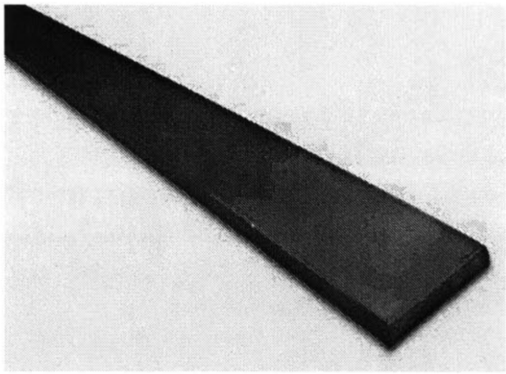
diameter: 1”



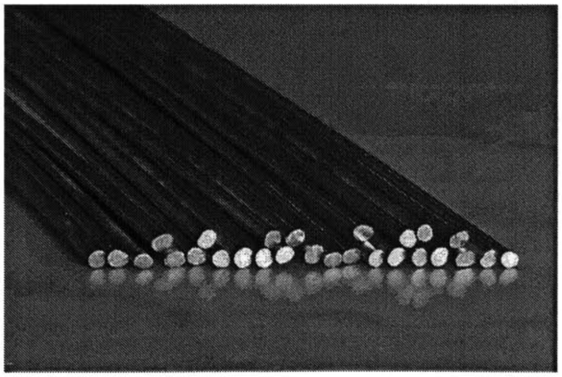
Aluminum Extrusion

1” x 1”

diameter: 1”

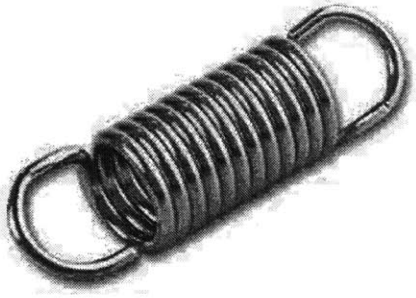


thickness: 1/4”, width: 2”

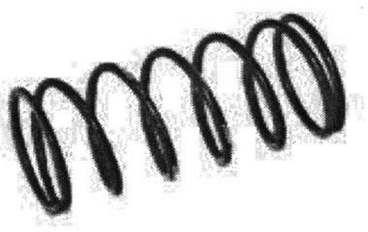


diameter: 1”

Lead Screw

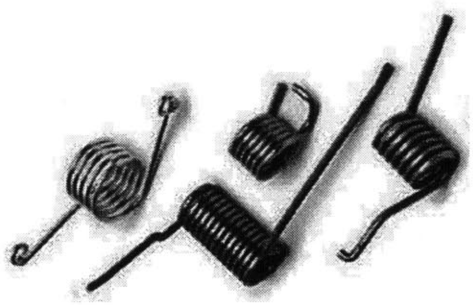


Extension Spring



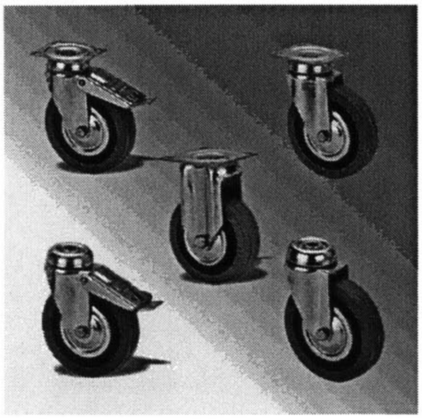
Compression Spring

Constant Force Spring

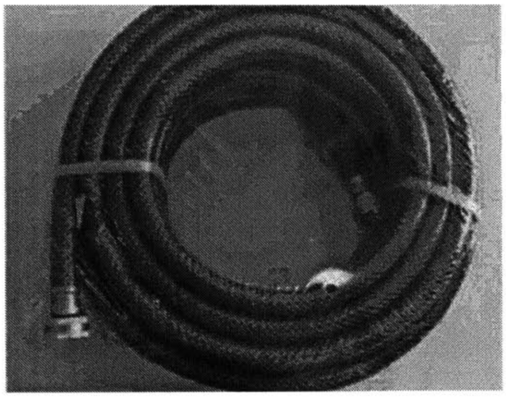


Torsion Spring

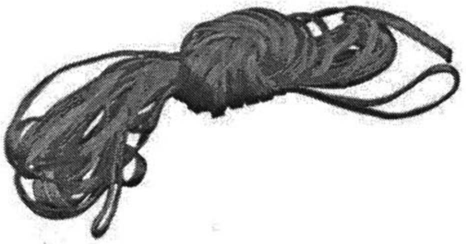
Ball Bearings



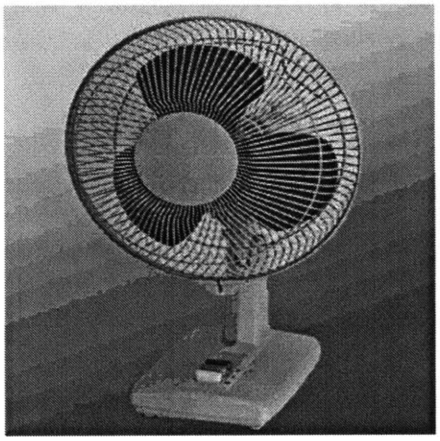
Wheels



Hose



Rope



Electric Fan

Broom and Dustpan

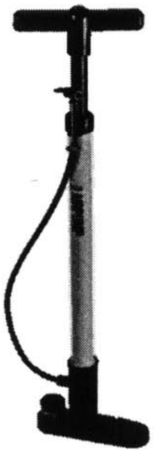
Cell Phone

Iron

Chair

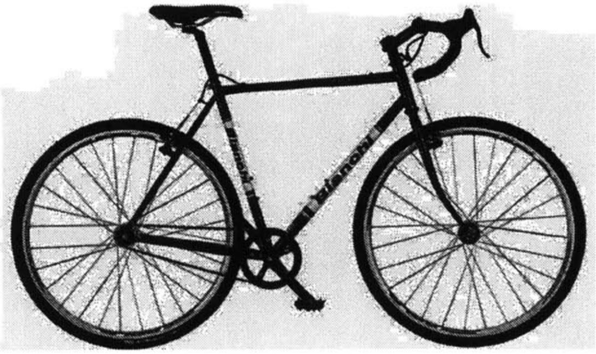
Buckets

Printer



Tire Pump

Market Umbrella



Bicycle