Impact of Prototyping Resource Environments and Timing of Awareness of Constraints on Idea Generation in Product Design

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Abstract

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

Keywords

International development, Product design, Prototyping, Resource, Supply chain, Innovation system

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1. Introduction

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

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

2. Previous Research

2.1. Prototyping Resource Environments

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

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

2.2. Supply Chains and Design

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

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

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

2.3. Resource Constraints and Idea Generation

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

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

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

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

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

2.4. What is Missing

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

3. The Research

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

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

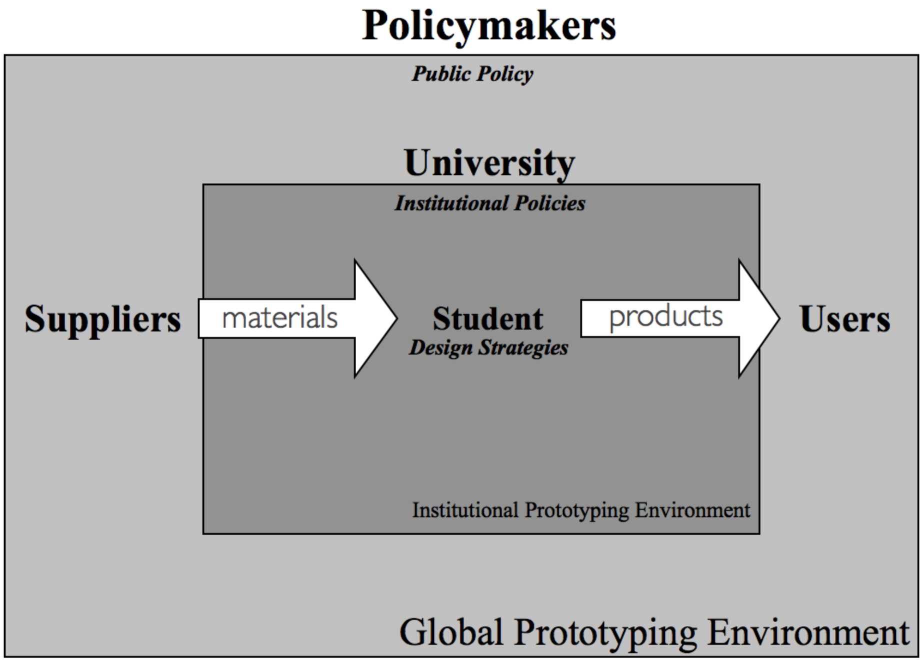


Figure 1. *Systems Model*

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

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

3.1. Research Questions

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

Q1: How does the prototyping resource environment that students learn in influence their design decisions and processes?

Q2: Assuming a constrained prototyping resource environment, how does the timing of information about the constraints influence early-stage design outcomes?

Q3: Does the prototyping resource environment that students learn in influence their design outcomes when they are put into a more constrained environment?

3.2. Hypotheses

H1: Students in more resource-constrained settings will have had more experiences adapting their designs to resource constraints.
Justification: In a more constrained environment, designers will have been more likely to be pushed off the "path of least resistance."

H2: "Thinking inside the box" and abstraction of the design before searching for materials will be more common in resource-constrained environments.
Justification: Constraints will shift the designer's frame of reference and cause them to consider other design processes as well.

H3: Knowing constraints earlier will result in more novel designs.
Justification: Not as easily able to reference existing technologies.

H4: 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.

H5: Knowing constraints earlier on will result in more appropriate concepts.
Justification: Without free-reign, designers will focus more on user needs for inspiration.

4. Case Study

A case study method was chosen over a general survey because the aim was not to describe product design in Mexico as a whole, but to better understand the influence of the local 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.

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.

4.1. Case Selection and Participants

The cases were selected to provide as large of a difference in prototyping environments 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.

Twenty-six undergraduate engineering students were recruited from two campuses of a university system in Mexico. In Campus A there were twelve total participants, two females, five mechanical engineering and seven mechatronic majors. Their education level ranged from 2 to 10 semesters completed, with the majority (66.7%) completing 7 to 8 semesters of undergrad. In Campus B there were fourteen total participants, five females, two mechanical engineering and twelve mechatronics majors. Their education level ranged from 4 to 8 semesters completed with the majority completing 6-7 semesters (64.3%). All aspects of the study were conducted in Spanish to maximize comfort of the participants and the fluidity of their written and oral responses.

4.2. Interviews

After the design experiment each student was interviewed for around 30 minutes, using a semi-structured format. The goal of the interviews was to learn about their typical design process by asking them to describe past projects. 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 divergent to convergent process.

4.3. Design Experiment

4.3.1. Task

The participants engaged in this experiment individually. The students were given a fictional 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 who were physically disabled due to diabetes). The participants were asked to include a list of materials and tools they would need to create a prototype of their designs, but were not asked to physically prototype anything during the experiment. 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. One experimental group was given this information at the beginning of the design session while the other received it halfway through.

4.3.2. 2x2 Factorial Design

The students in each campus were randomly assigned to one of two design processes. Half of the students from each campus followed each process.

Design Process1: Participants were given 20 minutes to generate ideas that satisfied the design prompt, with no material restrictions. They were then given the list of constrained materials and told that they had 20 more minutes to generate ideas.

Design Process 2: Participants were 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.

4.3.3. Procedure

Both groups were given a preliminary questionnaire to fill out, indicating their prototyping experiences. Participants were then 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. After the sketching exercise, both groups were given identical exit surveys.

4.3.4. Assessment of Resulting Designs

A web survey was conducted in order to obtain an outside viewpoint of the quality of the design concepts. 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) a three-point scale was chosen to force respondents to make a decision and to reduce the time required to complete the survey. For each sketch the participants were asked to respond to statements such as, “This design is original and uncommon,” with the options, “in disagreement,” “undecided,” and “in total agreement.” 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.

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 et al., 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. Evaluators were informed of the target user and general requirements of the prototypes, but were blind to the purpose of the study, information about the research variables, and most identifying factors of the inventors except for language as the survey and sketch notations were written in Spanish.

29% of the survey 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. 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.

5. Results

The results of the interviews and the design experiment were analyzed by Campus (A or B), the design process the participants followed during the experiment (Process 1 or 2), and the combination of the campus and the design process. In the presentation of the results, the four experimental groups will referred to as Campus A-Process 1, Campus A-Process 2, Campus B- Process 1, and Campus B-Process 2.

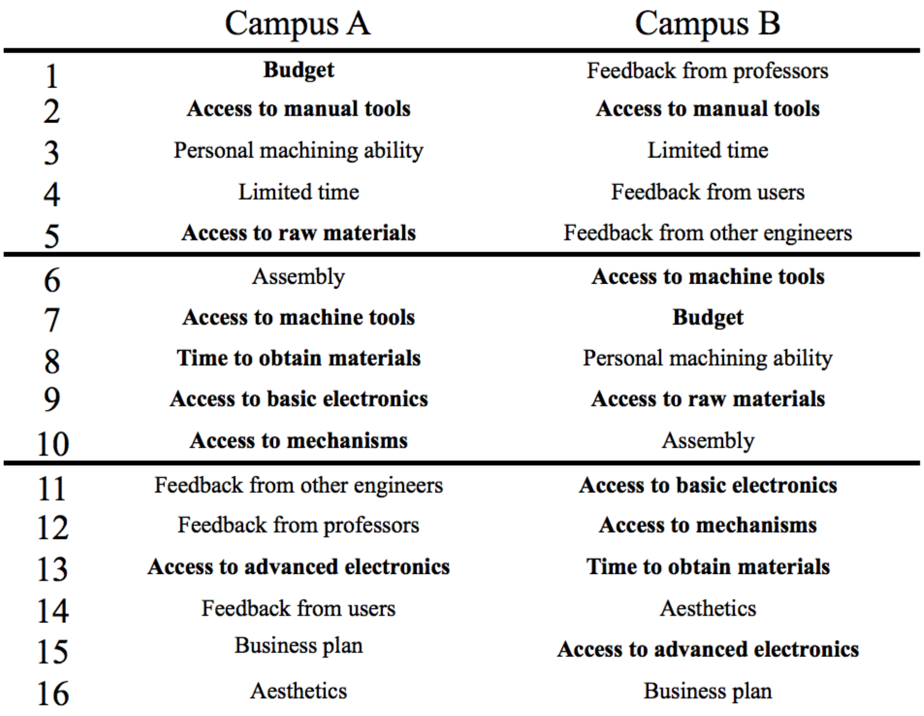
5.1. Prototyping Resource Environments

Both campuses are located in metropolitan areas in central Mexico with similar levels of economic development. Some of the main industries in the region where Campus A is located are metals, chemicals, electronics, and textiles and there are a number of automotive assembly factories and 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 a city that is home to numerous industrial parks and factories of multinationals in the automotive, aerospace, and consumer product industries. The recent economic growth rate of the region is above the national average. The campus itself had three spaces with prototyping equipment, and the institution pays for the majority of prototypes.

To understand how students in these campuses perceived their prototyping environment, participants were asked how much sixteen different factors influenced their design process, on a seven-point scale. Three of the top five factors in Campus A and one in Campus B were related to the prototyping environment while seven of the top ten most influential factors in Campus A were related to resources, compared to four 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.

Table 1. Factors influencing the design process (factors related to the prototyping environment are in bold)



	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

The two campuses are in similar standing on the general spectrum of design environments in both Mexico and around the world, and it is not the goal of this study to declare one resource “poor” and one resource “rich.” However, for clarity in the following discussion it is necessary to note that one is relatively more resource constrained than the other. The results from site visits, interviews, and questionnaires with students and professors from both campuses led the author to conclude that students in Campus A are relatively more constrained by their prototyping resource environment than students in Campus B.

5.2. Impact on Product Design Process

Even if the design is similar to past prototypes, students in Campus B tended to buy their own new 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 have 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 three months to arrive so they decided to make the device with only sensors. However, the sensors they had did not have the range they wanted so they bought a few simple sensors and combined them to mimic 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.

The dominant strategy discussed in the design literature 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 2. This is a divergent process in the ideation stage, which converges before construction.

An issue can occur 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, depicted in (b) of Figure 2. 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 2. Participants from Campus A discussed instances of following all three of these design processes, while students in Campus B tended to report following the traditional process. The results are consistent with Hypotheses 1 and 2.

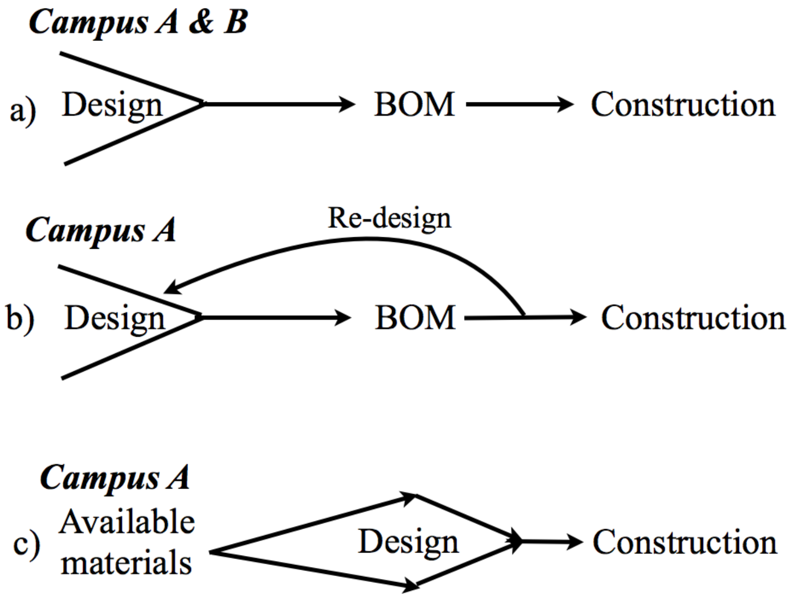


Figure 2. Design Processes Typically Followed in Each Campus

5.3. Impact of Timing of Resource Constraints

In the interest of economy, only results for the novelty and the appropriateness metrics are shared in this paper. The results of the other metrics echoed these findings.

5.3.1. Novelty

For the novelty portion of the evaluation, evaluators on Mechanical Turk were asked if they agreed with the statement, “The design is original and uncommon.” 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 (Figure 3). An example of a design scoring lower on the novelty metric is the skate-chair, which is essentially a reclined wheelchair (Figure 4).

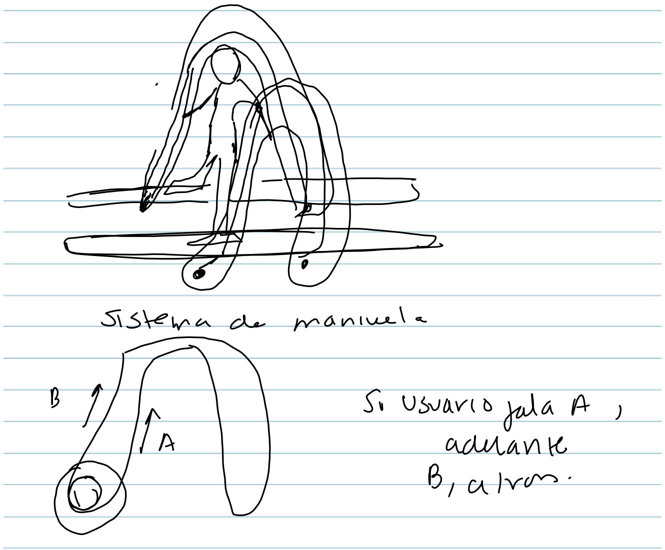
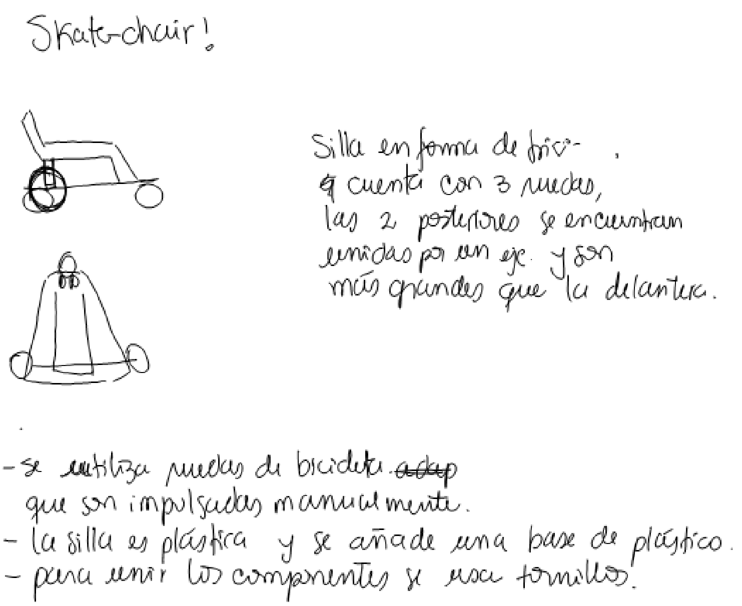


Figure 3. Example of a concept that earned a relatively high novelty score



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.

Figure 4. Example of a concept that earned a relatively low novelty score

A two-way ANOVA analysis of the average novelty of sketches produced per participant while constrained revealed statistically significant Campus effects (p=0.0357). On average, participants in Campus A produced more novel results while constrained than Campus B did, which is consistent with Hypothesis 4. Interestingly, participants in both campuses produced designs with similar novelty when they were constrained at the beginning, while being constrained later had a positive effect on Campus A and a relatively negative effect on Campus B, compared to being constrained earlier in the design process. However, these trends were not statistically significant and therefore the data supporting Hypothesis 3 is inconclusive.

5.3.2. Appropriateness

For the appropriateness metric, evaluators were asked if they agreed with the statement “The concept is appropriate for the user and the context described in the design prompt.” An example of a design that scored highly on the appropriateness metric is a wheelchair with an electric elevator to lift the seat (Figure 5). An example of a design that scored lower on the appropriateness metric is an electronic arm for separating components (Figure 6). Since the user in the design prompt had limited mobility in his legs, this device does not clearly address his problem.

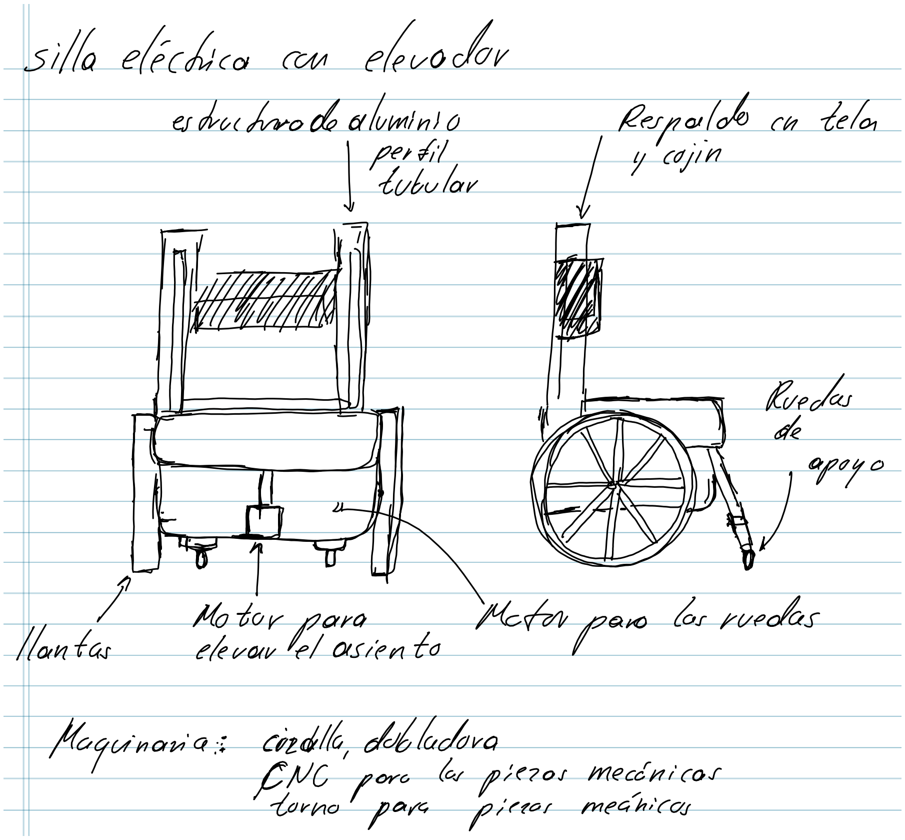


Figure 5. Example of a concept that earned a relatively high appropriateness score

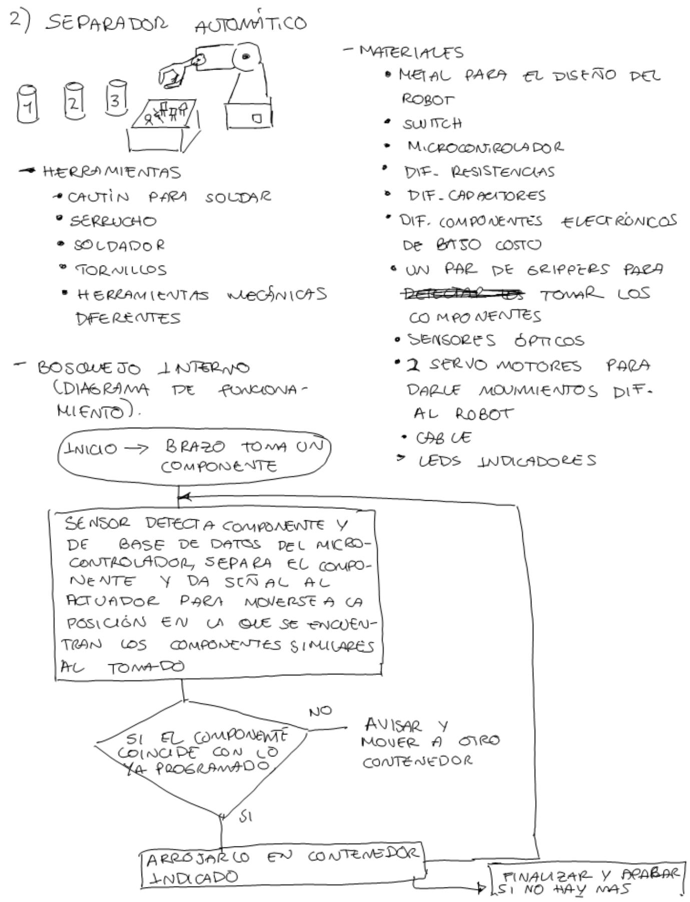


Figure 6. Example of a concept that scored a relatively low appropriateness score

A two-way ANOVA analysis conducted on the average appropriateness of the designs produced by participants while constrained revealed statistically significant interaction effects (p=0.0002). Participants in Campus A on average produced more appropriate designs when they were constrained halfway through while participants in Campus B on average produced more appropriate designs when they were constrained at the beginning.

The result of an interaction effect goes against Hypothesis 5 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 Campus A-Process 1 and Campus B-Process 2 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 Campus A-Process 2 tended to generate more ideas that were less likely to be on the market, and therefore it was probably more difficult for evaluators to judge if the devices would be appropriate to the user and context. Students in Campus B-Process 1 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.

5.3.3. Novelty and Appropriateness

Many design studies examine not only at novelty and appropriateness as separate metrics, but are interested in the combination, as most commercially successful designs will be both new and useful. An ANOVA test based on the average 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 on average when they were constrained halfway through while Campus B produced more novel and appropriate designs on average when they were constrained at the beginning.

A common design strategy is to generate an initial pool of ideas and then select one to pursue (Ulrich and Eppinger, 1995), so in order to not penalize students who had generated some initial lower-scoring designs, another analysis was conducted, only considering the highest scoring design produced 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.

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

6. 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 Campus B-Process 1 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 appeared to become too fixated and had more difficulty adapting. This result has been mirrored in anecdotes from 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 then have to “make it work.”

The relatively higher scores of the Campus B-Process 2 group compared to the Campus B-Process 1 group when they were constrained could be explained by the different frames of reference that were encouraged by the different timing of awareness of the constraints. The Campus B-Process 2 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, Campus B-Process 2 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 and Smolkov, 2006; López-Mesa et al., 2011).

Interestingly, the opposite effect occurred in Campus A, where the group that followed a divergent to convergent process (Campus A-Process 1) scored relatively higher on the metrics than their peers in the group that was constrained from the beginning (Campus A-Process 2). 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 Campus A-Process 2 were designing within a design space and frame of reference provided by the list of materials, the students in group Campus A-Process 1 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.

6.1. Implications for Theory

6.1.1. Timing of Awareness of Constraints

Few studies have looked at the timing of awareness of constraints and its impact on design outcomes. The case studies presented in this paper suggest that even when a group of engineers are designing with the same set of resources, the timing of their awareness of those constraints could have a large impact on the resulting designs. More importantly, while many design studies look to describe an “optimal” process, the findings of this study suggest that perhaps processes that are optimal in some settings may be suboptimal in others. By selecting participants who were used to designing in different contexts, this study also revealed insights that studies with a more homogenous participant population may miss.

6.1.2. Prototyping Resource Environments

Given that this investigation was structured as a case study with a small group of participants, there are limitations in the generalizability of the results. However, this study provides a systems framework for understanding and analyzing prototyping, product design, and design outcomes in a university setting, which can be adapted and applied in future studies.

This systems perspective of prototyping can help to unveil interaction effects that could be lost at a smaller scale. Most studies on prototyping referenced in this paper are at either an organizational scale or an individual scale and therefore capture only a component of the puzzle. This study combined analysis at a macro and micro level to expose interaction effects and potential new areas for research.

6.2. Implications for Practice

6.2.1. Fostering "Entrepreneurial" Engineers

The results of this study suggest 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 an engineer's dominant design process, and encouraging students to complete design projects with a variety of ideation processes could potentially lead to better outcomes, depending on the nature of the design challenge.

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 et al., 2008). Preparing product designers for rapidly changing environments may also depend on creating systems that help foster and support adaptive innovation and universities can play a substantial role in the formation of entrepreneurial students (Bransford, 2007; Rasmussen & Sørheim, 2006). Even in settings where resources cannot be augmented or changed, studies have shown that teaching design methods have had an impact on invention (Girón et al., 2004) and that improving learning capabilities can increase the capacity of small firms to exploit their resources in order to innovate (Amara et al., 2008).

During the interviews, the students shared their experiences working on class and personal projects, and their professors could have played an influential role in reinforcing or discouraging certain design processes. In these case studies, comments from professors about the design processes they saw on campus seemed to align with the processes their students described, even though the design curriculum in both campuses focuses on the traditional divergent to convergent design process. However, it is entirely possible that certain professors or mentors may have encouraged students to try other processes as well, that perhaps they saw as beneficial for producing designs in that prototyping resource environment. For example, the interviews revealed that in cost conscious laboratories, professors often constructed their curriculum to focus heavily on sketching and CAD modeling before any prototype was built, an economic tradeoff that has also been captured in the literature on the economics of experimentation (Thomke, 1998). A case study focused on the influence of resource environments on engineering professors could be an interesting direction for future research.

6.2.2. Innovation Policy

Policymakers and universities can potentially improve their innovation systems by analyzing and manipulating the local and national prototyping resource environments. 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. However, this system design may be suboptimal because it appears that it can decrease the adaptability of designers. A stronger policy may be to incorporate a laboratory design and design curriculum that encourages exposing students to the world of available technologies, while also requiring students to complete design exercises with varying levels of resource constraints.

For policymakers looking to develop an ecosystem of innovation, whether at a firm, university, country or international level, this research suggests that taking into account material supply chains and capital goods used in early-stage design could help to explain design outcomes. 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 or expanding access to useful supply chains can help promote more novel and appropriate design outcomes. This analysis can be coupled with existing surveys of local and national capacity to investigate ways to improve innovation systems and competitiveness in Mexico (Solleiro & Castañón, 2005) or any other country.

6.3. 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. Analyzing team discussions may lead to more insights on the thought process that occurs when solving these types of problems. 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.

This study could be replicated in any country, but Mexico was chosen 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 of a similar study could be informative 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. Conclusions

The findings from this research study have supported some of the hypotheses initially posed, while some findings were inconclusive:

H1: Students in more resource-constrained settings will have had more experiences adapting their designs to resource constraints.

True. In this study, students in more resource constrained settings reported re-designing more often after discovering that a desired design was not feasible given resource constraints.

H2: "Thinking inside the box" and abstraction of the design before searching for materials will be more common in resource-constrained environments.

True. Interviews with students in more resource constrained settings revealed more instances of adapting more complex designs so that they could be created using simpler, locally available parts.

H3: Knowing constraints earlier will result in more novel designs.

Inconclusive. There was no statistically significant effect of timing of awareness of constraints on novelty alone. However, participants who knew about constraints earlier on in the design process tended to produce sketches that scored higher in combined novelty and appropriateness.

H4: Students with more practice working with constraints will develop more novel concepts.

True. Participants who were accustomed to working with constraints on average generated more novel ideas than their peers who were used to a less constrained environment.

H5: Knowing constraints earlier on will result in more appropriate concepts for the user.

Inconclusive. Statically significant interaction effects were found, which suggests that the impact of the timing of awareness of constraints could have depended on the participant's normal prototyping environment.

The most compelling results of this study, however, are not the individual findings but the interaction among the findings. These case studies have suggested that there are more complicated interaction effects involved. The data suggests that the timing of awareness of resource constraints could impact designers differently depending on their usual prototyping environment. Circling back to the first question posed at the beginning of this paper, is design really universal? The findings of this study seem to suggest that we should be searching for *locally* optimal design processes instead of one *globally* optimal process.

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. The literature on 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 and greater investment) 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 probable when both ideologies are combined, as the growing number of success stories from emerging markets have shown.

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 can 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 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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