Understanding the Roles of Low-fidelity Prototypes in Engineering Design Activity

Hadi Ali, Arizona State University, Polytechnic campus

Hadi Ali is a doctoral student in Engineering Education Systems and Design at Arizona State University.

Dr. Micah Lande, South Dakota School of Mines & Technology

Micah Lande, Ph.D. is an Assistant Professor and E.R. Stensaas Chair for Engineering Education in the Department of Mechanical Engineering at the South Dakota School of Mines & Technology. He teaches human-centered engineering design, design thinking, and design innovation courses. Dr. Lande researches how technical and non-technical people learn and apply design thinking and making processes to their work. He is interested in the intersection of designerly epistemic identities and vocational pathways. Dr. Lande received his B.S. in Engineering (Product Design), M.A. in Education (Learning, Design and Technology) and Ph.D. in Mechanical Engineering (Design Education) from Stanford University. He was previously an Assistant Professor in the Engineering and Manufacturing Engineering programs and Tooker Professor for Effective STEM Education at the Polytechnic School in the Ira A. Fulton Schools of Engineering at Arizona State University.

Understanding Practical Ingenuity Through the Roles of Low-Fidelity Prototyping in Engineering Design Activity

Introduction

Practical ingenuity is demonstrated in engineering design through many ways. Students and practitioners alike create many iterations of prototypes in solving problems and design challenges. While focus is on the end product and/or the process employed along the way, this design methodology study combines these interests to better understand the product and process through the roles of initial prototyping through the creation of such things as alpha prototypes, conceptual mock-ups, and other rapid prototypes. We explore the philosophy behind the purposes and affordances of these low-fidelity prototypes in engineering design activity. We share a historical case study to illustrate aspects of low- and high-fidelity prototyping. A synthesis of different perspectives from literature allows the authors to identify issues surrounding such prototyping in a classroom setting to establish an integrated understanding to characterize prototypes for areas for further study.

Two research studies are described to explore the roles of low-fidelity prototyping in engineering design activity. A study using student prototyping examples is shared to connect the research to practice. Then, an analysis of textbook presentations of prototyping is also shared to both provide a possible basis for this gap and an opportunity to bridge this gap. By better understanding the literature basis for low-fidelity prototyping, how it is practiced by students in a course, and how textbooks present prototyping as a concept, this paper can help identify areas to improve teaching of this core engineering design topic and support the development of student engineers practicing practical ingenuity.

Background: Literature

Studying prototyping (activity) and prototypes (artifacts) is a way to better understand design thinking and how students and practitioners learn and apply a problem-solving process to their work. Prototyping can make readily evident and explicit (through act of creating and the creations themselves) some of the thinking and insights of the engineering designer into the design problem. Initial, low-fidelity prototypes are characterized as prototypes that are incomplete and lacking more elaborate depictions containing all the fine details of the design. It can be a quick and efficient means to explore drafts and iterations of ideas, essentially sketching in materials. The underpinning of this work is that prototyping, as a process, is an act of externalizing design thinking, embodying it through physical objects. It reflects one's thinking about design through a design process, and also a learning process. It can serve to both develop a design idea but can also inform the educator about how an individual or team navigates their learning experience.

According to various studies, prototyping is considered to play an essential role in the design process [1, 2, 3]. For example, the process of prototyping can bring design issue that alternative approaches to design cannot [4]; can enable designers' hypothesis testing [5]; and facilitate the communication within the design team while keeping the client involved in the design process as well [6]. Prototypes can be used as learning vehicles [7, 5] as designers refine ideas while interacting with them [8]. The term, "Experience Prototyping" has been proposed to refer to prototyping that enables stakeholders to gain insight of the problem-solution space through experiencing the interaction with the porotype [9]. In this sense, they are the primary feedback provider for designers on their ideas [10].

While several prescriptive frameworks have been developed to describe what prototypes prototype and the role of prototype, the role of *low-fidelity (Lo-fi) prototypes*, specifically, lacks sufficient attention. We will present prototyping rather as an holistic mindset that can be a means to approach problem solving in a more accessible manner. It can be helpful to apply this sort of mindset approach from these initial problems understanding through functional decomposition to quickly communicate and learn by trial and building in learning loops to oneself, with an engineering design team, and to potential stakeholders outside the team.

Although claims for the importance of prototyping and its centrality to designing are ubiquitous (e.g., [11, 12, 13]), little attention has been given to carefully understand lo-fi prototyping [14] specifically. The act of prototyping involves the externalizing of design thinking and the embodiment of ideas through physical objects. Ultimately, prototypes become representations of ideas. The notion sounds simplistic, unexacting and intuitive; however, the evidence-based grounding in design research with regards to the cognitive and affective processes that enable prototyping to provide insight [15], and reflectively learn design [16] are lacking [17]. Although previous researchers in design studied brainstorming [18, 19], sketching [20, 21], design documentation [22] as well as prototyping [4, 11, 23], the study of lo-fi prototyping specifically has been limited to studies of user interaction design (e.g., [5, 7]). Moreover, design educators show varied understanding of the utilization of prototyping in design education. Limited opportunities are provided to students to improve their conception of what a prototype is or what it can do to make leaps in the design activity. In a study of students' conceptions of prototyping, students reported their "actual" design process as different from a "formal" design process [14] and where prototyping was underutilized. They also indicated that they started the design process with the understanding that they were working on a final product as opposed to an artifact under iteration; only when a problem was encountered students retracted to characterize their physical artifact as a prototype. In another study of faculty conceptions of prototyping [REF UNDER REVIEW], some design educators described the lack of their ability to provide concrete feedback on students' prototyping, limiting the utility of students' prototyping as learning vehicles into the design process.

With these points in mind, this research to practice paper attempts to provide an integrated understanding of the centrality of lo-fi prototyping in the design process, with an illustration of early findings of an on-going study that of the effect of lo-fi prototyping on design activity in an academic setting. While many design educators may consider lo-fi prototypes as important, the process of lo-fi prototyping is considered a primitive activity that required little attention. We attempt to establish crucial, often over-looked aspects of the process, to improve understanding of the activity of lo-fi prototyping. We provide the following specific rationale, grounded in literature, for this study and research agenda.

Issue #1: Lo-fi prototypes are not being studied as a way to test ideas

In design courses, the focus tends to be on a final, functional product. Lo-fi prototypes do not have an intrinsic value; they lack a way of assessment; and they are overlooked by the students and the educators alike. Studying prototypes and prototyping is one way to studying design thinking. “The reason for prototyping is experimentation,” explains Tom Kelley and David Kelley of IDEO, the innovation company: “[is that] the act of creating forces you to ask questions and make choices” [24]. Prototyping provides insights into the design problem that other approaches to design cannot provide. Although understood as primitive representations of ideas, both students and educators overlook the notion of substantive ideation [25]. The lack of connection between form and function in prototyping, and the deep understanding of the relationship between parts was illustrated in a study of MIT undergraduate designers who, in a single-session, materials-constrained design challenge, only attempted to visually resemble generic devices, making “pre-Archimedean” errors [26].

Issue #2: Lo-fi prototypes are not introduced within context, lack sufficient exemplars

Examples of lo-fi prototypes are lacking. As opposed to being an essential part of iteration in design, lo-fi prototyping is being introduced and practiced by students as a haphazard activity. The rationale of how a current version of a prototype might insightfully inform what to do next is not emphasized [25]. One essential reason for this lack of understanding of the role of lo-fi prototyping is the lack of a clear definition, through cases and examples, of the insight it may provide to the design process [27, 28]. Design cases are needed to collect evidence of lo-fi and be framed as “practical ingenuity.” Examples, when accompanied by explanations of design decisions, allow the unpacking of early designs and the understanding of how an interim prototype evolves into a final product. The cases provided in this paper are aimed to depict expert strategies in various contexts [29]. Without cases, students may not experience rich design studies of improving ideas on prototypes in a systemic way. Therefore, this paper illustrates how lo-fi prototyping exists in practical cases in real-life engineering.

Issue # 3: Lo-fi prototypes are not introduced in a scaffolded, structured way

In design activities where empathy is emphasized, lo-fi prototypes become hard to make because a designer may be challenged with the question of “what is to be tested?” [30]. Similarly, when aspects of a complex system need to be prototyped, the system needs to be decomposed to its essential elements, raising the question of “what to prototype” [3]. In both cases of empathy and complexity, lo-fi protypes are built with the aim of seeking feedback. Scaffolded prototyping, suggested in [31], provides a systematic way “to support self-regulated learning by offloading feedback from the instructor to students’ evaluation of their own built prototype in the context of iterative feedback from a user.” Different levels of lo-fi prototypes allow answering, in addition to the question of “what to prototype,” the question of “why” in order to learn the motivation in each step on the scaffold (even when students or educators think that they know the answer [30]). But in order to inform the answering of “What?” and “Why?” studies are lacking on “How?” lo-fi prototypes are actually best achieved. Therefore, this paper presents initial findings of a study aimed to exploring how students perceive lo-fi prototyping in design activity.

<u>Issue #4: Lo-fi prototypes are not present, elaborately introduced, in text books</u>

Design and engineering textbooks provide prescriptive (as opposed to descriptive) approaches to the design process. Prescriptive models in design provide a pre-defined sequence of activities and assumes a high-quality solution of followed as suggested. In comparison, descriptive models of design characterize what designers actually do while designing, without reinforcing any sequence *a priori*. While designing involves the working on ill-structured problems with no single solution, prescriptions of the design process assumes a rather linear, predictable process. Consequently, in design courses, engineering design activity is pursued with a mismatch between content and pedagogy, where students are left with the impression that designing is a natural competency of good designers [32]. Therefore, this paper describes the gap in introducing prototyping generally, and lo-fi prototyping specifically, in introductory engineering textbooks and in the context of design.

Collectively, the described issues provide grounding for an attempt to understanding the role of lo-fi prototypes in engineering design activity. This paper introduces primary findings of an on-going qualitative research study.

Background: Illustrative Cases: Lo-fi Prototypes and Practical Ingenuity

Three historical cases provided are used to illustrate how lo-fi prototyping is manifested in real-life engineering. In providing these cases, we suggest, in light of methods and theoretical perspectives drawn from Science and Technology Studies (STS), that cases such as these can be used to enrich the introduction of this overlooked topic to the students. Technological determinism provide a robust framework for analyzing sociotechnical interactions in the context of prototyping.

Products have a life with their users; a user builds a relationship and develops an experience with a product once bought. We might argue that we have different kinds of experiences when we buy a new product versus pre-owned products (e.g., a used car). Some historians of technology assumed that a technology transforms the society, in a one-way relationship. However, equally important is the way that society transforms the technology, Figure 1. *Lo-fi prototypes to be successful, in this sense, should evoke scenarios of the future, telling stories and communicating future visions.*

Consider, for example, the impact of the automobile in rural America [34]. Significant studies have focused on the impact that the automobile had had on technology, business and society, ever since Henry Ford introduced his Model T in 1908. However, less obvious are the different interpretations that users gave to this technology, Figure 2. In this sense, technology becomes socially constructed [35]. A market started to emerge offering home auto kit that allowed users to modify the Model T for specific needs. In response, the Ford Company started in 1916 delivering a complete line of cars, trucks and tractors, accelerating the development of the new products through a non-traditional starting point—a modified low-fidelity prototype, Figure 3. The idea of "product warranty" started to emerge as Ford warned dealers that warranties of their products would be voided if altered by the users.

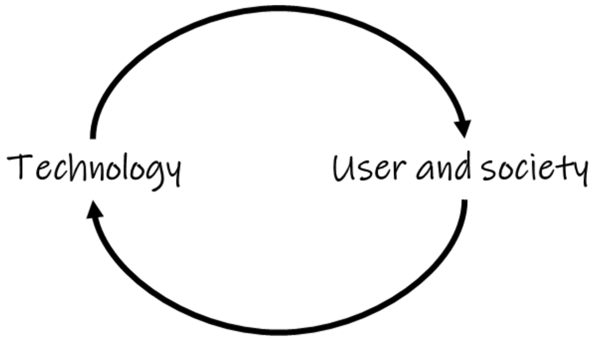

Figure 1. "Products" of technology, and "users" of technology: a continuous interaction.

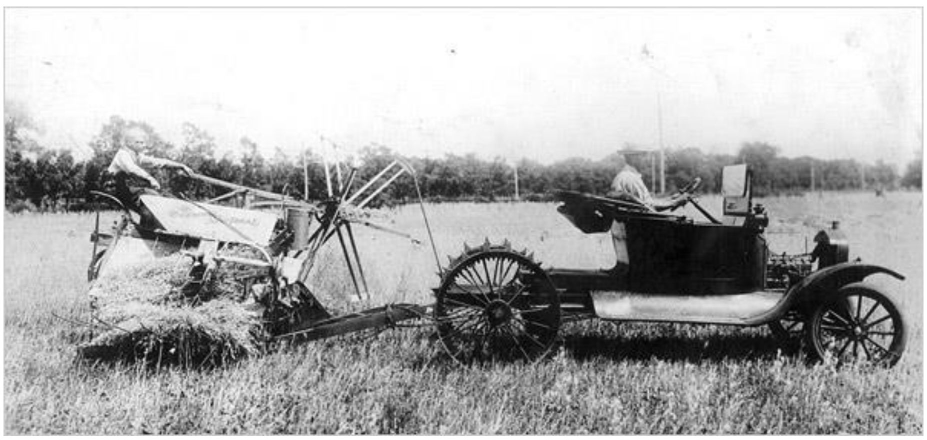

Figure 2. Interpretive flexibility: The same object can mean different things to different users. Here, an example of unintended, but useful use of the Ford Model T as an engine-powered tractor [36].

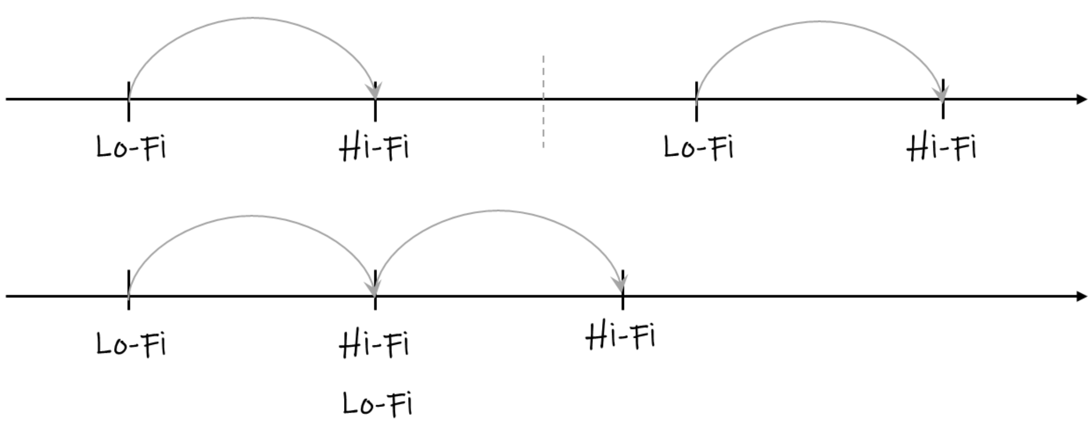

Figure 3. The altering of the Model T to fit farmers needs accelerated the development of trucks and tractors by Ford through low-fidelity prototypes created by the users.

One view of technological development assumes that new ideas present themselves with a predictable, self-determining trajectory—the ideology of technological determinism. However, the new trends of empathy and human-centeredness of design convince us that human choice, not technology, moves history. *Lo-fi prototypes, therefore, should be built with an explicit emphasis on having an element of understanding the impact on human users, both directly and indirectly.*

Consider the impact of automation trends in the 1970's on the labor market [37]. The introduction of numerically-controlled machines, for example, has had social impacts on workshops floor workers, who viewed the new technology as a threat to their jobs. Frederick Taylor introduced the idea of scientific management as a way for managerial authority to control production by managers who did not necessarily understood the technology they managed [38]. The numerical control technology was supported by the Air Force with early versions subcontracted to Bell Aircraft, John Parsons, and engineers at MIT. Early, low-fidelity prototypes were received with little enthusiasm by machine tool builders [37].

The complexity of the early prototypes was faced with tremendous troubles and lack of interest from both the workers and the aircraft companies, which were the early adopters of the technology. The result was the development of one component of the required technology; that is, the development of numerical control, while the other, more important, and human-related piece of technology was not developed in parallel with the same pace; that is, the record playback (the process through which a worker's movements were recorded when machining a piece of equipment so that they could be later programmed for numerical control) [37]. Melman observed the following,

> "*If one wants to alter our technologies, the place to look is not to molecular structure but to social structure, not to the chemistry of materials but to the rules of man, especially the economic rules of who decides technology.*" [39]

Furthermore, *lo-fi prototypes shape policies*. Consider, for examples, the wheelchair design. Wheelchairs is one form of assistive technologies that include seeing for the sightless, speaking for the voiceless, and hearing for the deaf. Originated in 1918 when a mining accident in California started the idea with the company Everest & Jennings, the first wheel chairs foldable but bulky. The first wheelchairs weighted 90 lbs. However, after dominating the business for 50 years, E&J lost their lead in the business after stopping to attend to customer needs. However, and inspired by another accident experienced by Marilyn Hamilton in 1978, she asked her fellow pilots to build her an ultra-light wheelchair.

The initial prototypes, weighting 26 lbs, were sporty and fun to ride. The early versions pushed Hamilton to start Quickie, the wheelchair company. A new market for wheelchair emerged; with sales jumping from half a million in 1960 to 1.2 million in 1980, with a cost of the wheelchair dropping from about $1000 to about $250-$300 [40]. The increase in wheelchair production resulted in disabled individual asking for more independence: curb cuts, lifts on busses, parking spots, going to college, taking jobs and getting married. Assistive technologies like wheelchairs, talking computers and cochlear implants pushed the need for universal designs for both products and systems in society. "Most disabled people are beginning to believe they have a right to technology. It’s no longer a luxury,” Karen Franklin observed, a member of Rehabilitation Engineering and Assistive Technology Society of North America [40, p. 236].

Overall, when understood correctly, the social construction of technology represents one form of interaction with lo-fi prototypes. Lo-fi prototypes are not always defined by how they look, or if they actually work; they are understood by what they do. This involves understanding issues around function and context. Therefore, and transferring the observations discussed in the three historical cases, if we wish to effectively link the studying of prototyping (as an activity) and prototypes (as artifacts) we should allow lo-fi prototypes to tell stories and communicate visions; allow empathy to understand the direct and indirect implications of design paradigms; and evoke emotional needs.

Research Questions: Two Studies

In this paper, we try to illustrate how practical ingenuity is demonstrated in engineering design through multiple ways. We separate this effort into two research questions.

Initially, we focus on the “How?” question of lo-fi prototypes; more specifically, our research question is *how do students perceive low-fidelity prototyping in design activity?* Answering this question informs the answering of “What to prototype?” and “Why?” Here, early reflections by students are provided as a result when lo-fi prototypes are introduced in a scaffolded, structured way.

The second study is a content analysis of five engineering design textbooks to address the research question of *how students are instructed on the role of prototyping?*

Research Methods for Student Prototyping Activities

As a research to practice paper, this paper attempts to extend the tools through which design activity can be analyzed. Analyzing the design activity from one perspective only would defy the purpose of this paper of understanding the purposes and affordances of lo-fi prototypes from different perspectives. Being an overlooked topic, it is necessary to investigate the creation of new frames as a key to this design practice. Assuming one approach to qualitative research in design can be “quite problematic for a design research community that has been shy of oversimplifying its object of study, and cherishes multiple perspectives and rich pictures” [33]. Therefore, this study is still in an exploratory phase. In addition, we describe an ongoing analysis that utilizes thematic analysis in qualitative research to analyze students’ reflections on a design activity. On-going research to analyze the transcripts provides the early observation discussed.

Results: Low-Fidelity Prototypes as Practiced by Students

In an attempt to understand students’ approaches to low-fidelity prototyping, we asked students to create three different prototypes of “an exercise machine that saves time and space.” The idea behind the project was to push the students beyond the machine itself, thinking about larger contexts of exercising and healthy living—a readily available machine in a dorm room, for example, can save time for the students not needing to walk for the gym if it is designed in a way not to take much space as well. We tried to avoid using terms such as a “foldable machine” so that we do not restrict the range of ideas. Also, the reason for specifying the building for three different prototypes is to reinforce the notion that prototyping is a process of ideation—we are not seeking a functional prototype; instead, we aimed to restore the centrality of prototyping in the design process to allow the divergent-convergent thinking modes of the students.

The activity was deployed in a sophomore class on use-inspired design, asking students to work on the activity in teams of four. Below are samples of students’ work and their reflections on the activity.

In one of their concepts, Team 1 designed a “Bedmill;” a combination of bed and treadmill. The design is an exercise device that is incorporated into a bed, Figure 4.

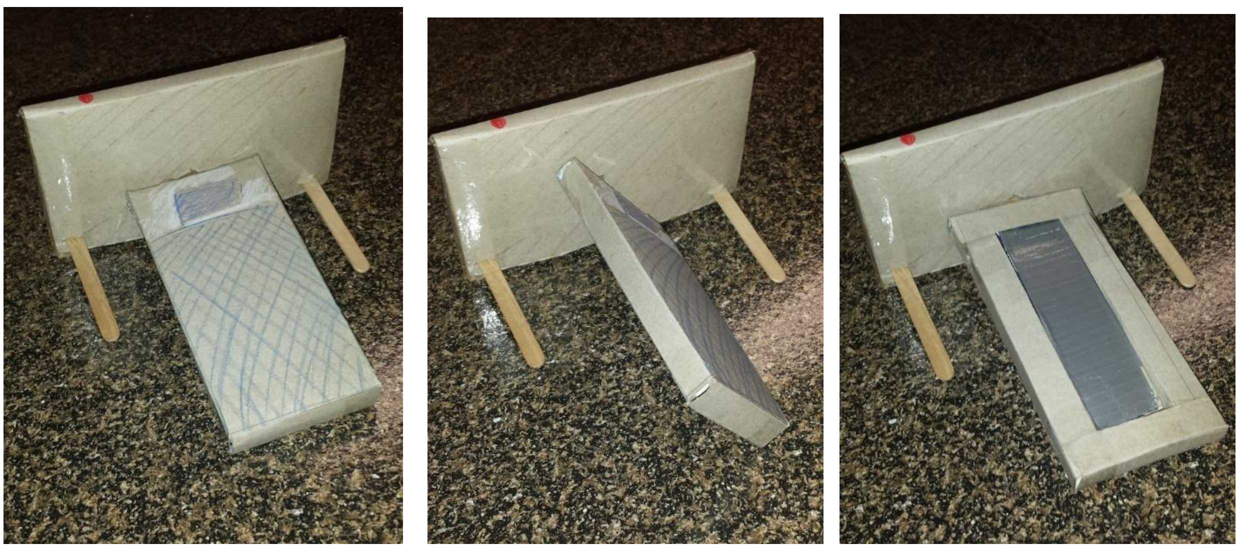

Figure 4. Team 1's concept: A "Bedmill"

Reflecting on the activity, a member of the team provided the following:

> *“I actually found this to be a difficult section. I’ve always had a creative mind and wild imagination, so coming up with ideas has never been difficult. What I found to be challenging was having to follow the process and have provide documentation and rationale for every idea. If someone approached me on the street and asked to give them ideas for an exercise machine that is space saving I could give them a half dozen ideas right off the top of my head. The downside of my traditional approach is that there is no documentation of the development of the idea and no corroborating evidence to show the idea meets any of the actual customer’s needs…*
>
> *“When I got to the prototyping stage the people I was working with decided since there were three of us and three prototypes that each person would build a different one. The idea I chose to develop was the “Bedmill.” The idea was to try and incorporate the exercise device into a preexisting piece of furniture so that there would be no extra space taken up, thus saving the maximum amount of space. While the “Bedmill” is the most*

mechanically complex of the three ideas (requiring the gearing and motors to flip the bed) it does offer a very large tread and convenience.

"The looks-as prototype I built was made mostly from cardboard, popsicle sticks, and tape. I used duct tape for the tread to try and make it look visually distinct. I also did a little coloring on the cardboard to make it pop a bit."

The ideas, the understanding of the design problem, and the achieved learning about design through the process seems to have been amplified in the students' practice of prototyping. Another example of time- and space-saver exercising machine is a "weight vest," Figure 5. In this design, the team envisioned a vest to be worn by the user as he or she performs cardiovascular activities.

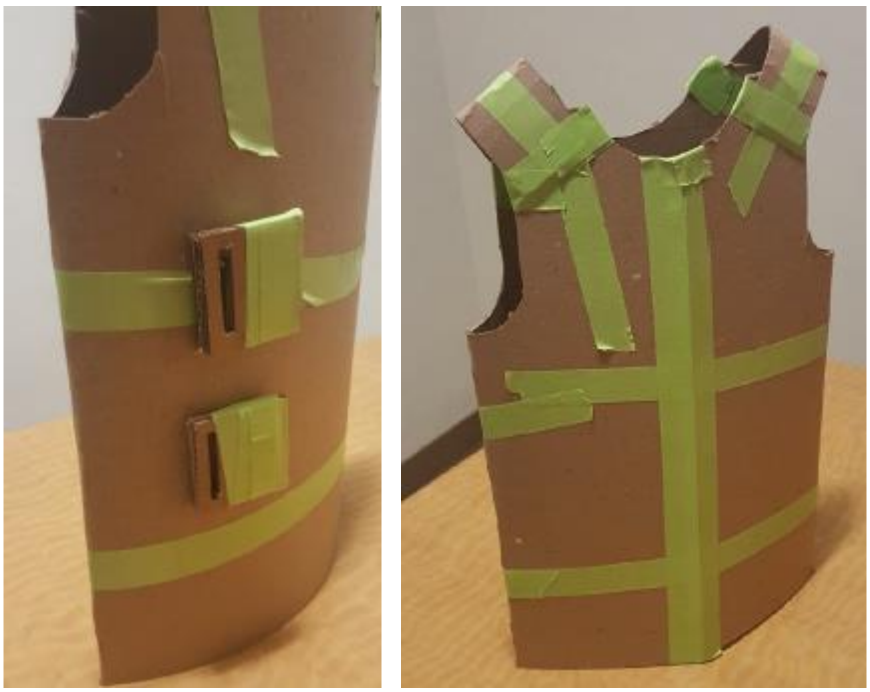

Figure 5. One of Team 2's concepts: A "weight vest"

"*Overall, everyone of the concepts was built to success. However, a build that affords the designer the ability to see into the design for assembly phase of a product, is valuable and became apparent while we were building these mockups. While building these concepts, each individual design showed its promise and its shortcomings. I personally have come to the conclusion that aspects from both the door frame resistance band and the convertible grip resistance system should be combined into a design that prevails over them individually. The\ two designs have aspects that can be combined into a greater version. I would love to build a secondary phase of design and would combine the solid attributes of both designs and lead us down a path to a concept that would satisfy user needs in a fashion superior to the rest. I also learned that when designing things, the ability to actually build something is extremely\ important. How function effects form, is something that I will always take into consideration at every turn of the design process.*"

This team was able to generate a range of ideas that are different from each other. Design as a learning activity [16, 41] has been found to be a process where students, as developing designers, move back and forth between the creative process of designing and the reflective process of analyzing the approach being taken [42]. However, the examples provided and the sample insights provided by the students point to the need for effectively linking the studying of prototyping (as an activity) and prototypes (as artifacts) through the use of lo-fi prototypes.

Research Methods for Content Analysis of Prototyping Descriptions in Textbooks

Finally, we use content analysis as a qualitative research method to organize and analyze data. In this case data sources are represented in five engineering and design methods textbooks which are considered some of the most common in the field. The textbooks selection was informed by a study that utilized textbooks as a way to scaffold design activity [44]. The study found that allowing students to read a textbook's description of the design process results in a higher quality of students' design work, better transitions and more design strategies [44]. The content analysis of text book included the following steps: index search, content search, grouping and categorizing.

Results: Prototypes Descriptions in Textbooks

Despite the centrality of design to the engineering profession, neither design nor prototyping are cited as a separate attribute in the Engineer of 2020 reports [43]. Clear attributes of "practical ingenuity" and "creativity" are emphasized. It is insightful to explore the presence of low-fidelity prototyping in design textbooks, in an effort to further explore how links between design as a process and design as a product are being formally introduced to students.

In one of the widely cited references in engineering design, Pahl & Beitz provide a skeleton for the lifecycle of a product, moving from market/need/problem, to product planning, to design and development, to production and assembly [45]. There is no reference to prototyping but in one page when talking about detail design in "Flow of work during the process of planning and designing":

> "*In many cases, models and prototypes have to be developed even during the conceptual phase, particularly when they are intended to clarify fundamentals questions in, say, the precision engineering, electronics and mass production industries. In heavy engineering, on the other hand, if prototypes are needed at all, they must often be preceded by an almost complete run through of the detail design phase.*" [45, p. 69]

Another work by French on conceptual design for engineers lack any reference to prototyping [46]. The "block diagram of design process" is show to flow from conceptual design to embodiment of schemes, described as one where "the schemes are worked up in greater detail, and if there is more than one, a final choice between them is made" [46, p. 3]. When discussing insight as part of conceptual design, the author observes the following:

> "*It is a common experience to find that an idea, worked on long and hard, has some basic flaw which is instantly recognized at a later stage because insight into the problem has improved.*" [46, p. 5]

The process of how this insight develops and where it comes from, as well as characterization of how manipulating objects such as prototypes aids in the development of insight are not discussed.

A common engineering design introductory textbook that emphasizes materials and processing is the one by Dieter [47]. The author recognized the difficulty of prescribing methods for the embodiment of design compared to prescribing methods for conceptual design "because of the variety of issues that enter into the development of the configuration and performance of components" [47, p. 227]. However, the link between low-fidelity prototypes and conceptual design as a way of ideation is not described:

> "*The general objectives of the embodiment phase of design are the fulfillment of the required technical function, at a cost that is economically feasible, and in a way that ensures safety to the user and to the environment."* [47, p. 227]

While Dieter thoughtfully articulates that "the role of the prototype in product development is often overlooked" [p. 250], he continues to describe the prototype as a "full-sized working model that is as close as possible to the design of the product that will be marketed" [p .250]. Discussion of low-fidelity prototypes is absent, beyond this synopsis that appears in a chapter on modeling and simulation.

In another textbook entitled *Exploring engineering: An introduction for freshmen to engineering and the design process* provides no mention of prototyping at all. On discussing the "benefits of a hands-on design project" the authors provide the following:

> "*A basic understanding of the challenges involved in manufacturing a product is essential for producing a successful design. The best way to appreciate that fact at an early stage in your career is to manufacture a design yourself. The lessons to be learned are universal. Don't expect your design to work on the first try. Leave a lot of time for testing. Complicated designs take a lot longer to build and have a lower probability of success. If you have a choice of manufacturing a part yourself or buying it, buy it.*" [48, p. 311]

Other references have worked on providing algorithmic ways to approach creativity in design; e.g. [49]. In a book entitled *Design engineering: A manual for enhanced creativity*, the authors suggest a way "to quantify creativity, codify inspiration, and document a process seemingly based solely on intuition." This stream of research is beyond the scope of this exploratory study.

While prototyping is present in many other books, lack of presence of low-fidelity prototyping, specifically, as an integral part of the engineering design process in some of the common introductory engineering textbooks raises questions as the expectations of design education in project-based learning [50].

Discussion

In this paper, we aimed to provide as a holistic mindset for lo-fi prototyping that goes beyond assuming that a lo-fi prototype is simply a “rough draft” of the design. Through examples from practice, students’ work, and textbooks, we were able to illustrate a gap that exists in the way lo-fi prototyping is present in the design process. Non-traditional cases from practice pointed to examples where lo-fi prototypes *should evoke scenarios of the future, telling stories and communicating future visions; should be built with an explicit emphasis on having an element of understanding the impact on human users, both directly and indirectly*; and how*, low-fidelity prototypes shape policies*. Samples from students’ work from a prototyping activity provided early evidence for the efficacy of such approaches to restore the centrality of prototyping to the design process. Finally, through a survey of some textbook on engineering design, we were able to see the absence of this centrality.

Future Work

We aim to build on these ideas, by first analyzing the students’ work from the described activity in a more structured way. Ultimately, the goal is to carefully structure scaffolded prototyping, as suggested in [31], as a way to provide a systematic way “to support self-regulated learning by offloading feedback from the instructor to students’ evaluation of their own built prototype in the context of iterative feedback from a user.” However, the issue should not be pursued, as we saw, without attention to both function and context to effectively link prototyping (as an activity) with prototypes (as artifacts) through lo-fi prototypes.

References

[1] Deininger, M., Daly, S. R., Sienko, K. H., & Lee, J. C., "Novice designers' use of prototypes in engineering design," *Design Studies*, no. 51, pp. 25-65, 2017.

[2] Kelley, T., & Littman, J., The ten faces of innovation: IDEO’s strategies for defeating the devil’s advocate and driving creativity throughout your organization, Crown Publishing Group, 2006.

[3] M. Schrage, Serious play: How the world’s best companies simulate to innovate, Harvard Business Press, 2013.

[4] Yang, M. C., & Epstein, D. J., "A study of prototypes, design activity, and design outcome," *Design Studies,* vol. 26, no. 6, pp. 649-669, 2005.

[5] Hartmann, B., Klemmer, S. R., Bernstein, M., Abdulla, L., Burr, B. and Robinson-Mosher, A., & Gee, J., "Reflective physical prototyping through integrated design, test, and analysis," *Proceedings of the 19th annual ACM symposium on User interface software and technology (ACM),* pp. 299--308, 2006.

[6] De Beer, D. J., Campbell, R. I., Truscott, M., Barnard, L. J., & Booysen, G. J., "Client-centred design evolution via functional prototyping," *International Journal of Product Development,* vol. 8, no. 1, pp. 22-41, 2009.

[7] B. Hartmann, Gaining design insight through interaction prototyping tools, PhD Dissertation, Stanford University, 2009.

[8] Lim, Y., Stolterman, E., and Tenenberg, J., "The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas," *ACM Trans. Comput.-Hum. Interact,* vol. 15, no. 2, pp. 1-27, 2008.

[9] Buchenau, M. and Suri, J.F., "Experience prototyping," *roceedings of the 3rd conference on Designing interactive systems: processes, practices, methods, and techniques, ACM,* pp. 424-433, 2000.

[10] A. Jørgensen, "On the psychology of prototyping," in *Approaches to Prototyping*, Springer Verlag, 1984, pp. 278-289.

[11] Houde, S., & Hill, C., "What do prototypes prototype," *Handbook of Human-Computer Interaction,* vol. 2, pp. 367-381, 1997.

[12] Menold, J., Simpson, T. W., & Jablokow, K. W., "The Prototype for X (PFX) Framework: Assessing the Impact of PFX on Desirability, Feasibility, and Viability of End Designs," *ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference,* 2016.

[13] B. Moggridge, Designing Interactions, The MIT Press, 2007.

[14] H. Ali and M. Lande, "Why make it? Understanding undergraduate engineering students' conceptions for the purpose of prototyping in engineering design activities," in *IEEE Frontiers in Education Conference*, Salt Lake City, UT, 2018.

[15] Lawson, B., & Dorst, Design expertise, Oxford, UK: Architectural Press, 2009.

[16] Beckman, S. L., & Barry, M., "Innovation as a learning process: embedding design thinking," *California Management Review,*, vol. 50, no. 1, pp. 25--56, 2007.

[17] Gerber, E., & Carroll, M., "The psychological experience of prototyping," *Design Studies,* vol. 33, no. 1, pp. 64-84, 2012.

[18] P. Paulus, "Groups, teams and creativity: the creative potential of idea generating groups," *Applied Psychology,* vol. 49, pp. 237--262, 2000.

[19] Diehl, M., & Stroebe, W., " Productivity loss in idea generating groups: Toward a solution of the riddle," *Journal of Personality and Social Psychology,* vol. 53, pp. 497-509, 1987.

[20] Purcell, A., & Gero, J., "Purcell, A. T., & Gero, J. S. (1998). Drawings and the design process: A review of protocol studies in design and other disciplines and related research in cognitive psychology.," *Design studies,* vol. 19, no. 4, pp. 389-430, 1998.

[21] Suwa, M., & Tversky, B., "What do architects and students perceive in their design sketches? A protocol analysis," *Design studies,* vol. 18, no. 4, pp. 385-403, 1997.

[22] A. Dong, "The latent semantic approach to studying design team communication," *Design Studies,* vol. 26, no. 5, pp. 445-461, 2005.

[23] Dow, S., Heddleston, K., and Klemmer, S.R., "The Efficacy of Prototyping Under Time Constraints," *Proceedings of Creativity & Cognition, ACM,* 2009.

[24] K. Collias, "Unpacking Design Thinking: Prototype," 2014. [Online]. Available: http://knowwithoutborders.org/unpacking-design-thinking-prototype/. [Accessed April 2018].

[25] Newstetter, W. C., & McCracken, W. M., "Novice conceptions of design: Implications for the design of learning environments," in *Design knowing and learning: Cognition in design education,* Elsevier Science, 2001, pp. 66-77.

[26] C. Miller, Learning through designing: Connecting theory with hardware in engneering education. Unpublished doctoral thesis., Cambridge, MA: MIT, 1995.

[27] N. Cross, Design thinking: Understanding how designers think and work, Berg, 2011.

[28] Goel, V., & Pirolli, P., "The structure of design spaces," *Cognitive Science,* vol. 16, no. 3, p. 395–429, 1992.

[29] Barlex, D., & Wright, R., "Using the internet as an information gathering tool for the design and technology curriculum," *IDATER '98,* p. 160–168, 1998.

[30] Lewrick, M., Link, P., & Leifer, L., The design thinking playbook: Mindful digital transformation of teams, products, services, businesses and ecosystems, Hoboken, NJ: John Wiley & Sons, 2018.

[31] M. Lande, "Scaffolded Prototyping Activities in Product-Based Learning Engineering Design," 2017. [Online]. Available: https://istl.asu.edu/presentations/scaffolded-prototyping-activities-product-based-learning-engineering-design. [Accessed April 2018].

[32] Kelley, T., & Kelley, D., Creative confidence: Unleashing the creative potential within us all, Currency, 2013.

[33] K. Dorst, "The core of 'design thinking'and its application," *Design studies,* vol. 32, no. 6, pp. 521-532, 2011.

[34] Kline, R., & Pinch, T., "Users as Agents of Technological Change: The Social Construction of the Automobile in the United States," *Technology and Culture,* vol. 37, no. 4, pp. 763-795, 1996.

[35] D. E. Nye, " Shaping communication networks: Telegraph, telephone, computer," *Social Research,* pp. 1067-1091, 1997.

[36] L. Brook, "Mr. Ford's T: Versatile Mobility," The New York Times, 20 July 2008. [Online]. Available: https://www.nytimes.com/2008/07/20/automobiles/collectibles/20FORD.html. [Accessed February 2019].

[37] D. Noble, "Social Choice in Machine Design: The Case of Automatically Controlled Machine Tools," *Case Studies on the Labor Process,* pp. 18-50, 1979.

[38] T. Frederick, Scientific management, New York: Harper & Brothers, 1947.

[39] S. Melman, "The impacts of economics on technology," *Journal of economic issues,* vol. 1, no. 9, p. 71, 1975.

[40] J. P. Shapiro, "Screaming neon wheelchair," in *No pity: People with disabilities forging a new civil rights movement*, New York, Three Rivers Press, 1993, pp. 211-236.

[41] P. Fong, "Knowledge creation in multidisiplinary project teams: an empirical study of their dynamic relationship," *International Journal of Project Management,* vol. 21, no. 7, pp. 479--486, 2003.

[42] C. Owen, "Design research: building the knowledge base," *Design Studies,* vol. 19, no. 1, pp. 9-20, 1998.

[43] Bailey, R., & McFarland, M. E., "Prototyping and the Engineer of 2020," *International Journal of Engineering Education,* vol. 34, no. 2, pp. 567-573, 2018.

[44] Atman, C. J., & Bursic, K. M., "Teaching engineering design: Can reading a textbook make a difference?," *Research in Engineering Design,* vol. 8, no. 4, p. 240–250, 1996.

[45] Pahl, G., & Beitz, W., Engineering design: a systematic approach, New York: Springer, 1996.

[46] M. French, Conceptual design for engineers, New York: Springer, 1999.

[47] G. E. Dieter, Engineering design: A materials and processing approach, McGraw Hill, 2000.

[48] Kosky, P. G.; Wise, G.; Balmer, R. T.; & Keat, W. D., Exploring engineering: An introduction for freshmen to engineering and the design process, Elsevier, Inc., 2006.

[49] N. P. Suh, Principles of design, New York: Oxford University Press, 1989.

[50] Dym, C.; Agogino, A.; Eris, O.; Frey, D.; and Leifer, L., "Engineering design thinking, teaching, and learning," *Journal of Engineering Education*, vol. 94, no. 1, pp. 103--120, 2005.