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Difficulties Student Engineers Face Designing the Future*

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Design can change the world. Growing environmental and social concerns about the role we play as world citizens and caretakers of the planet have given rise to a green environmental movement and concerns of sustainability. But normative notions of sustainability only attack these problems in incremental ways. Another suggested approach, geared towards real impact and breakthrough innovation, is to shift the frame of these growing issues of our time in a different way. Rather than plainly engineer better solutions and implement better technology, this paper describes design and design thinking education practice and student examples that seek to change the context dramatically, break the mold of current means of thinking about sustainability, and the difficulties student engineers face in doing so. In examining mechanical engineering students doing design work in the context of a graduate level mechanical engineering design course at Stanford University, this paper will highlight some difficulties students have in framing, conceptualizing and designing for the future.

Keywords: design thinking; engineering thinking; future thinking

1. INTRODUCTION

DESIGN IS UNIQUE among disciplines and vocations in that it can significantly impact the world around us. The acts of observing, conceiving, and implementing a change make design and engineering design important activities for those concerned about the world in which we live. Growing environmental and social concerns about the role we play as world citizens and caretakers of the planet have given rise to a green environmental movement and sustainability. Sustainability calls for a mindful caretaking of Earth's limited resources. A triple bottom line of environmental, financial, and social concerns often frames the sustainability argument [1]. Sustainability is defined as the ability to sustain or keep; inherent therein is a notion of an extended period of time over which the fearful negative impact could fall. These time frames are usually general and abstract, i.e., *this will affect the next generation or the planet for years to come*. For designers and engineers, issues of sustainability manifest in decisions such as the materials selected and lifecycle planning for products. In addition to a concern regarding a *carbon* footprint there is also a concern for a *stuff* footprint [2].

Most sustainability efforts are a means to engineer or implement a change. These are all certainly noble and important efforts that will have measurable impact on our world around us. This optimization approach to make efficient established methods of production or product service families, by its nature, leaves most changes resulting in mere incremental innovations on existing practices.

Considering that this is not enough, another suggested approach, geared towards *sustained* real impact [3] and *sustained* breakthrough innovation [4], is to shift the frame of these growing issues in a different way. Rather than plainly engineer better solutions and implement better technology, this paper describes design and design thinking education practice and student examples that seek to change the context dramatically and break the mold of current means of thinking about sustainability. Engineering students should be asked with each problem faced not just to re-engineer and re-manufacture but to re-visit the solution space and re-define the questions asked in the first place.

This is design and design thinking [5], especially relevant for the ill-defined, wicked problems [6] of today. This is designing for the future, for tomorrow—past conventional product release cycles, to have an even greater impact on our world for generations to come.

By examining mechanical engineering students doing design work in the context of a graduate level mechanical engineering design course at Stanford University (Mechanical Engineering 310 *Global Team-Based Design Innovation with Corporate Partners*), this paper will illustrate the benefits of the approach of breakthrough innovation through design thinking, as well as highlight some difficulties students have in framing, conceptualizing and designing for the future.

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2. MAPPING SUSTAINABILITY TO THE WAYS OF THINKING FRAMEWORK

Using the framework of the Ways of Thinking approach [7] we would be better able to put in context design and engineering activities to make real impact on green and sustainability issues. Previous attempts by the authors to classify student activities in the Mechanical Engineering 310 course have produced this working framework modeling 'Ways of Thinking' accessed by engineering students. As shown in Fig. 1, it is visually represented as a matrix showing relative position of Design Thinking, Engineering Thinking [8, 9], Production Thinking [10], and Future Thinking [11].

The activity of Design Thinking can be to *solve a problem* with the end results being an *idea* created. For Engineering Thinking *making a solution* results in an *artifact*. Production Thinking allows for the *remaking of a solution* with the results being *facsimiles* or plans by which to make copies. Future Thinking allows one to *reset the problem* with the outcome being a *question*. Along the Y-axis is a spectrum of incremental innovation to 'breakthrough innovation.' Along the X-axis is measurement of time.

By mapping where issues of sustainability might fall within the Ways of Thinking framework, we can see that engineering and production thinking encapsulate issues of sustainability. Material selection is something considered within the implementation step of the design process. Lifecycle manufacturing concerns are something considered in the production thinking activities. Engineers do not usually address sustainability with the mindsets of future thinking or design thinking.

Students are designing the future and designing for the future. Within this Ways of Thinking framework, changing the norm can be done a couple of ways:

- Future Thinking: Change the *question.*
- Design Thinking: Change the *solution* or solution space.
- Engineering Thinking: Change the *artifacts* or prototype in the implementation.
- Production Thinking: Change the *manufacturing process.*

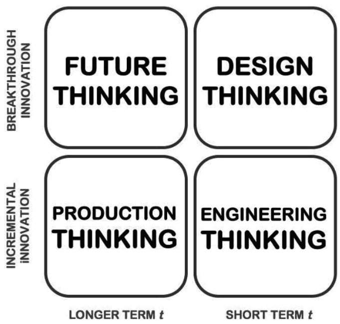

Fig. 1. Ways of thinking framework for engineering design projects.

The first two are in the functional space, the last two in the physical space. Existing sustainable design practice and sustainability efforts focus on engineering and production issues. These are incremental innovation. Efforts to reframe and redesign, in contrast, result in a change in paradigm and possibilities.

3. THE MECHANICAL ENGINEERING 310 COURSE

Mechanical Engineering 310 *Global Team-Based Design Innovation with Corporate Partners* [12–14] is a core mechanical engineering and design product-based-learning [15] course for first-year masters students in mechanical engineering. It features student teams working on corporate sponsored authentic industry design projects. Over time, prompts provided by sponsoring companies have evolved from manufacturing, testing, and assessment equipment to product focused problems [12]. In recent years, problems that industry have presented focus less on traditional mechanical engineering or mechanical design systems problems but rather on more general wicked and ill-defined problems [6]. Even for those projects that have been of a more normative mechanical engineering type project, over the course of the academic year, student teams take their projects and place them out into the future. Some projects end up being designed for today, some for the short-term of up to five years out, and others are placed more than 5 or 10 years out in the longer term [14]. Some of these projects are *scoped* for the future from the starting prompts, while others are *envisioned* for the future and arrived there through the students' work over the course of the year as evidenced by the deliverable. Example project topics from the Mechanical Engineering 310 course are listed in Table 1.

In each academic year, the course features approximately 10 projects with student teams and corporate sponsors. This paper reflects on the last four years of the course and uses student documentation, course deliverables, student observations, and student reflections to capture topics and themes that have students design for the future, and outlines the difficulties students have in reaching that task. Passages in sections IV and V are taken directly from student team documentation.

3.1 Learning goals and objectives

Nominally the learning goal of the course is to teach a design process to engineering students. The

Table 1. Example projects in mechanical engineering 3101

- The Car Co-Pilot of 2020
- The Future of Elderly Care
- Very Human Technology
- Novel Interaction Method

Mechanical Engineering 310 course is a capstone-plus [12], product-based learning experience. Most students have had a capstone design course experience [16, 17] from their undergraduate studies, but some [18] have described the Mechanical Engineering 310 course experience as better approximating industry practice.

The learning objectives of the course are to have students:

(1) Produce a preproduction proof of concept prototype of a refined solution from a given prompt.
(2) To be able to develop and evaluate engineering requirements.
(3) Foster team building and teamwork skills.
(4) To develop individual skills such as project management and planning.

3.2 Student concepts of a design process

Most students have previously been exposed to some design or design methodology. Their experience, though, is limited to learning what some of the design steps may be, practicing those techniques and habits, and using them to synthesize and culminate in their capstone engineering undergraduate experience. For most students, their conceptual understanding of the design process is a very simplified, linear one. As their hands-on prototyping activities and design learning occurs and students step through the design steps in the course, their design process representations become more nuanced, showing evidence of iteration and flexibility.

Students' concepts of the design process develop from a novice, linear design process (Fig. 2) at the start of the course to something that is more iterative (Fig. 3) at the end of the course. (Student concept maps were collected at the start of the course and subsequently at the end of fall, winter and spring quarters.) Often, the students know their engineering content knowledge, but what's new is the concept of needfinding and observation in the fuzzy front end of the design process. Student concept maps of their typical design process change from first to second quarter to show inclusion of a person or user as part of the envisioned system. As students step through and experience their project work, their concept maps of the design process in mid-course as well as at the end of the course are understandably more developed. Student concept maps begin to show iteration and connection of design steps in a loop or continuing manner [19]. Some concept maps at the end of the course show a change from a routine step through the design process to something that is more adaptive. The example shown in Fig. 3 starts to show the design process as something that is less routine and more fluid and adaptable [20].

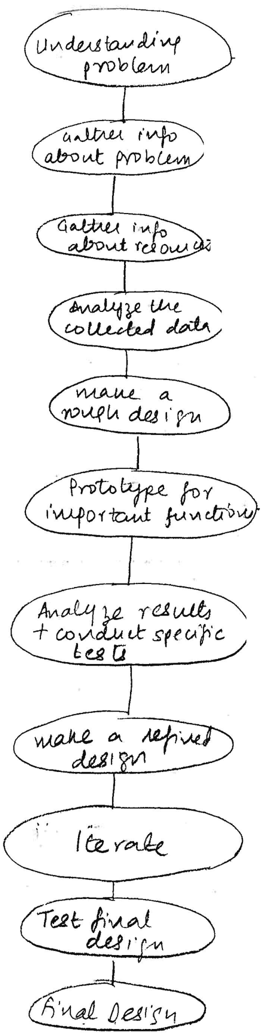

Fig. 2. Linear representation of student design process, at beginning of course.

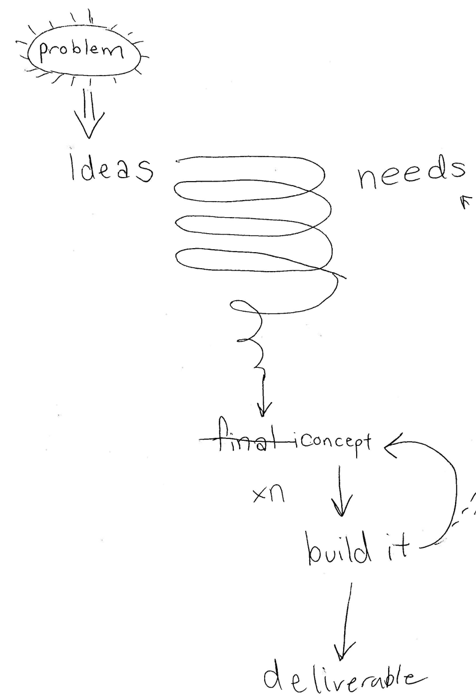

Fig. 3. Iterative representation of student design process, at end of course.

4. DIFFICULTIES STUDENTS FACE WITH PROJECT WORK

Students in the Mechanical Engineering 310 course, regardless of their particular project, have some difficulties in approaching and managing their design projects. The constellation of the course affords a strong support structure. Students work in teams of 3–4 students locally at Stanford and are matched up with similar teams of students at globally distributed university partner sites. They are provided with a sizeable project budget and a physical working space in a project loft. Students have regular weekly meetings with the teaching team consisting of Professors, Teaching Assistants and Consulting Professors with technical expertise. Student teams also have a coach from industry to consult on technical and team dynamics issues.

4.1 All hands-on

For many students this is their first extended and in-depth exposure to a hands-on engineering design project. With this new course experience, students have difficulties in managing the assignments and necessary collaboration. Every team works hard to prototype and iterate numerous design and engineering prototypes. Low cost and rapid prototyping and approach of *prototyping to learn* [21] pervade. Teams also struggle to define and redefine engineering requirements appropriate to their project. A student reflects on different approaches to problem solving:

> . . . In traditional engineering, pure knowledge is valued much higher than a vivid imagination. Even with my background in engineering, this class has taught me to believe that the imagination is more important than knowledge, and I have surprised myself. And I have surprised myself even more when the people around me believe it too. If and when the troubles arrive, this imagination kills those problems . . .

4.2 Teaming together

Working together in close collaboration with others is also somewhat of a challenge. Students are in the first year of their masters program, in their early twenties, without project experience; issues with project management, planning and communication are always learning experiences for student teams. A student reflects on the team experience and lists a few of the bumps along the way:

> . . . We were lucky. The team is effective and our efforts are often well-orchestrated (despite a lack of planning, lapses in communication, and ballooning stress levels) . . .

Students are introduced to a human centered design process with emphasis given to rapid prototyping and iteration. Moving from planning to doing so rapidly is often a switch in their usual practice for students.

5. DIFFICULTIES STUDENTS FACE WITH DESIGNING THE FUTURE

Students dealing with ambiguous future scoped projects have additional sets of difficulties in approaching, solving, and resolving their projects. As envisioned 5 to 20 years out in the future, the specificity in which their assignment is described is thereby much less specific—it is ambiguous [22].

5.1 Living with ambiguity

The ambiguity with which projects are defined is something that students find unsettling and most certainly are not used to. As engineers, they have been trained to eliminate ambiguity, not preserve it, and to minimize any existent uncertainties. For the most part, a student's work and graduate career have been framed in closed-end problem solving. One student reflects on experiences in the course:

> . . . I was sometimes frustrated by a lack of order and decisiveness in the project. I often feel like we spend a lot of time discussing ideas, and have a difficult time turning the ideas into actions that we can ultimately draw conclusions from and move forward . . . I'm all about execution and organization, while most of the other teammates prefer to preserve ambiguity. I've been very conscientious of the need to hold back on my desire to converge our ideas into a solution during the first quarter, and am still trying to figure out how to maintain the right balance between supporting new ideas while also making necessary decisions . . .

Students develop a multitude of different methods with which to cope with these difficulties. It is oftentimes that they resolve and arrive at novel and successful project outcomes. They use up valuable time and resources in their attempts, hesitant to take chances or make mistakes.

5.2 Understanding the problem

Future scoped projects often have nebulous noun phrases: *car co-pilot*, *elderly care future*, *very human technology, novel interaction method* (see Table 1). Student teams try to understand what these could mean and ground their benchmarking of current technology on what exists today. Students have a hard time constraining their problem space and spin their wheels trying to capture everything, noted by the following student reflections:

> . . . Our scope was from the very beginning too wide, and we should have narrowed it down a lot. Dispersing a field of ideas is a good thing—if the dispersion covers only one area. Our dispersion covered all the ideas in the world that relate to [the topic] . . .

> . . . I think the situation is that we (and I) have a lot of ideas, and a sense of where to go, but due to poor management we are not able to explore all the routes that we would like, or at least I would like, to explore . . .

5.3 Re-setting the problem space

A simple way in which students have ameliorated their own unease with an amorphous future-scoped project is to re-set [23], change or redefine their project direction and scope.

Re-defining the problem space: Through active design activity like benchmarking and experience prototyping, students come to re-define their project direction from the initial prompt. They may re-define the solution space to further constrain the possible solution set. As a student relates, it is not easy:

> . . . The seemingly simple task of defining our problem was very difficult and cumbersome . . .
>
> . . . We have come a long way from the beginning of the project, re-describing and refining the given assignment to better meet the needs on the market based on vast and thorough benchmarking . . .

Re-scoping the problem space: In contrast, re-scoping the problem opens up the problem space and expands to a broader allowance of what question the project is then attempting to address. It allows for more possible creative solutions. A student reflects on re-scoping their project due to new information from others:

> . . . We met a lot of people giving different inputs and wanting different things . . . Our team finally received the much needed inputs from [our corporate sponsor]. The additional information seemed to diverge a lot from the initial requirements given to us . . .

5.4 Paralysis of inaction

Frozen by no clear path: With amorphous future projects, student teams applying a normative design process do so in a way that is inefficient and causes them to spend extra time on early design steps when compared to other types of projects. The absence of a clear path sometimes renders the student design team rudderless:

> . . . At times, due to the number of different paths we could have taken in developing the [project] and a lack of firm criteria according to which to prioritize what we should spend our efforts on and what to prototype, time has not been spent as effectively as it could have been. However, I suspect this is normal considering how broad our initial project brief was . . .

Stalled by indecision: As a culmination of all the frustrations of the topics listed above, as time rolls by in the course, student teams face moments of increasingly seemingly important decisions. Sometimes inactivity is the safe way to go. A student recounts such a moment in their project:

> . . . progress slowed as team members were waiting if there's change in course. Indecision lasted for a week while waiting for feedback from the liaison. After a decision to proceed with [the concept] was made, the team woke up that next deadline is around the corner and lot of questions remained unanswered . . .

5.5 Technology as a panacea

Engineers are focused on the physical and possible. They have a techno-optimistic view of the world and stuff, technology and mechanisms are the lingua franca of the discipline. A cool gadget or gizmo (a Wii Remote, touch screen or a simple mechanism) is exciting and may sometimes serve as a distraction.

Faith in technology: Technology, correctly implemented, can solve most any problem. Or so an engineer might think. Sometimes the focus of the student design team was fixated on the role a piece of technology could serve:

> . . . Some things we have also discussed and agreed on are the need for [the component] in the future. This will be a big aspect of the project, since [the component] will be the most expensive part of our project so far. They will be a great aid for prototyping . . .

Technology not quite there: Dealing with future envisioned projects, student teams often seek out specific functionality that cannot yet be done with existing products or current technology. Oftentimes a functional system can be put together with an element of the system being completely oversized (like having a computer in the trunk of a car rather than a microprocessor) or even using the 'Wizard of Oz' technique [24] to pull off a completely engrossing experience. A student describes dealing with voice recognition as part of a project:

> . . . The decision was made early during spring quarter that voice recognition software would not be used in the final prototype. An early winter quarter prototype had demonstrated that voice recognition can be used to chat in a car, but the software took over an hour to train well, and even then was unreliable and slow. In addition, the design team did not have the resources to integrate voice recognition seamlessly into the other software being developed, and our attempts to integrate the technology in the short time frame given would have led to an overly complicated and unreliable system.
>
> Because we wanted a system that could be tested by real users, and demonstrated quickly to a large number of people at the end of the year design fair, we decided to use a transcriber. The transcriber would listen to an audio feed of the driver's voice and, using a custom programmed software application . . . type what was being said when buttons were pressed. During user testing and the design fair, we took turns transcribing what was said. We affectionately came to call this role 'the Wizard,' a reference to the man behind the curtain in The Wizard of Oz, who makes it seem that things are happening when they are actually being faked . . .

5.6 The future is bright and shiny

Once tasked with designing for the future, student teams often raise their expectations of how novel or innovative their solution should be. It is not for today—it is for tomorrow. They might judge their ideas more harshly or simply not think their ideas novel enough to move forward on:

> . . . Many of our weaknesses as a team were brought to light, namely, the ability to do original 'out-of-the-box' thinking. This is something that we are con-

stantly working on both as a team and as individuals. Now is the time to think foolishly and try crazy ideas that are impractical before we need to buckle down and start finalizing our plans—this is something that we need to embrace . . .

. . . Sometimes I can be so indecisive because I want to pick what's BEST, what's perfect, what everyone will like. My team reminded me that there isn't just ONE correct solution like in a multiple choice exam; that's the thing about design . . .

6. CONCLUSIONS

Breakthrough innovation is harder to accomplish than incremental innovation. The risks and rates of failure are greater but the rewards are greater as well. Considering concerns of sustainability and the potential and impact of design, design thinking and design engineering, it makes as much sense, if not more, to be concerned about how to design the future as minimizing the footprint of stuff on our world.

Training the next generation of student engineers to be able to develop and apply their judgment to such untenable issues seems like the best option we have.

Engineering students are hard pressed to consider not what could be done but, rather, what should be done. So what can be done to help? Programs like the Mechanical Engineering 310 course chronicled above help. Equipping technical students with a liberal, expansive education and basis in social and economic understandings helps.

For engineers and designers it helps to make them aware of concerns for the planet as well as the array of supports and barriers often found in student engineering work considering re-designing the future. To be aware, engage in reflection and strategic application of design steps, be empathetic and to prototype cheaply, early and often are all aphorisms that could help education and practice. The hope here is that both sustainability and sustained, breakthrough innovation through designing the future can benefit the whole world.

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