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From Engineering Design Research to Engineering Pedagogy: Bringing Research Results Directly to the Students*

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This paper describes how inductive pedagogical methods and findings from our design research were used in interactive engineering seminars to generate students' interest and motivation and to help students gain insight into design processes. We show how design process timelines, which are graphical representations used for mapping and analyzing individual design processes, can be effectively used as learning tools in the classroom. The activities and instruments we developed are explained, and we also relate our methods to established learning theory and pedagogical models, including topics in metacognition, project-based learning, and inductive learning.

Keywords: timeline; design process; engineering pedagogy; design thinking; design research; representations; inductive learning

1. INTRODUCTION

OVER THE PAST decade, researchers at the University of Washington's Center for Engineering Learning & Teaching (CELT) conducted research on engineering design processes [1–7]. Specifically, we studied how engineering undergraduates and experts solve engineering design problems. Our overall aim was to produce new insights about engineering design that could lead to improvements in curricula and classroom practices [8]. We endeavor to complement our research on design cognition and practice with further inquiry into practical applications of our findings.

In this paper, we discuss one of our instructional efforts to bring research findings directly into classrooms. We recently designed and implemented interactive seminars, wherein students in three project-based and capstone design courses analyzed some of our research data and developed their own insights. Those insights became the catalysts for in-depth discussions and comparisons to our research findings. We will begin by setting the context and describe a few of the pedagogies currently used in engineering education to teach and learn engineering design.

We will lead readers through our approach by presenting our research in much the same way we presented it to students in interactive seminars. We provide an overview of our design research, including how we collect, represent, and analyze data, and then describe the seminar activities. We will use student insights that were drawn directly from the seminars to anchor a discussion of our research findings.

2. TEACHING ENGINEERING DESIGN

The design process resides at the heart of engineering practice and therefore, it is critically important that engineering students develop a high degree of understanding and ability in this arena. However, saying it should be learned well is far easier than identifying how it should be taught. Design often entails complex and ill-structured problem solving that is distinguished by ambiguity, the existence of multiple solutions, and few, if any, procedural and declarative rules [9, 10]. Design problems are situated in real contexts [1, 2], involve social processes [11], and involve people with different perspectives (designers, technicians, users, etc.) from different disciplines (within and outside of engineering) working together to solve complex technological problems that address societal and consumer needs. The growing body of research on design thinking helps to elucidate these many aspects and is complemented by research on design learning [12].

2.1 Current approaches and knowledge for teaching design

No comprehensive, single approach for teaching engineering design exists. The literature contains learning theories and related pedagogies. These pedagogies draw on findings and experiences from many sources, including engineering design research, engineering education research, and the

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practical experiences of engineering educators and their students.

2.2 Project-based learning

Project-based learning (PBL) is a model for teaching problem-solving and is a highly effective approach for engineering pedagogy. Many engineering capstone and other project or design-oriented courses are grounded in the PBL model. Requiring a commitment beyond a single classroom meeting, PBL is intended to take students throughout the entirety of a problem-solving process [13]. This includes initially identifying and defining the problem, developing and evaluating solutions for the problem, and potentially implementing solutions [12]. Not all PBL projects allow this much student autonomy, as noted by Prince and Felder [14]. However, autonomy to choose projects and strategies is regarded as important for increasing motivation to learn. The PBL models endeavor to provide students with authentic engineering experiences, as collaboration and use of real-world problems are critical aspects to this approach. Moreover, PBL is grounded in learning theory such as Kolb's theory of experiential learning [14, 15]. The three key findings described in the National Research Council report, *How People Learn: Brain, Mind, Experience, and School*, also map well to PBL approaches [14, 16].

Prince and Felder [14] describe PBL methods as a form of *inductive learning*, wherein 'Instead of beginning with general principles and eventually getting to applications, the instruction begins with specifics—a set of observations or experimental data to interpret, a case study to analyze, or a complex real-world problem to solve' (p.138). Inductive pedagogies are intended to facilitate linking new learning to a student's prior knowledge, to create contexts for reflecting on preconceptions, to engender interest and motivation, to generate the need for further information, and to provide the right circumstances for filling information needs when they arise [14].

Project-based learning approachs are attractive because they can provide students with real design experiences and opportunities to reflect on the design process. PBL has also been shown to have additional benefits for engineering education. Dym, et al. noted that current research suggests that PBL education not only improves student learning but leads to improvements in student satisfaction, retention, and diversity [12].

2.3 Reflective discourse and representations

Other approaches for teaching engineering design focus on helping students develop cognitive skills that support engineers during the design process. A particular skill set for engineering students to acquire is the ability to engage in *reflection* or *reflective discourse* about their work. An aspect of metacognition, reflection is the ability to monitor and evaluate one's thoughts and actions during and after a cognitive task like engineering design [16–19]. Reflection can be triggered by an event that comes as a surprise to the practitioner or through deliberate action to monitor one's progress and direction. The latter is a recognized characteristic of expertise across many fields. Adams, et al. found that compared to freshman engineering students, senior engineering students engage more frequently in 'back-talk' with design problems by noting gaps in their knowledge and identifying new design requirements as the problem and solutions evolved [17]. This can also be described as an inductive learning process, in which those senior students were discovering for themselves the need for more information.

To understand where reflective practice comes from, it is important to recognize that design involves two types of necessary knowledge: (a) explicit, domain-related technical knowledge and (b) tacit knowledge of the *process* of design and an ability to deal with 'ill-structured' situations [20]. Research on expertise demonstrates that, in addition to committing to memory a great deal of specialized knowledge, experts 'have efficiently coded and organized this information into well-connected schemas' or integrative structures that help them link relevant aspects of their knowledge to new contexts [21] (p. 73). Explicit design knowledge includes a domain-specific language belonging to the community of practice in which the act of design takes place, and thus this language provides a framework for meaning-making [22]. Tacit knowledge (the understanding of the process) forms the major basis for reflective practice by providing multiple frameworks to assess not only the progress of the design process, but relevance of specific technical knowledge.

Promoting tacit knowledge development is a challenge. Assessing students' mastery of such knowledge is complicated, and it is assumed that pedagogical practices like PBL, active learning, and design studio will indirectly and implicitly address this learning [23]. Explicit, direct teaching of the skills necessary for reflective discourse is another approach. Hirsch and McKenna used a series of reflective exercises in which freshman and senior students identified abstract factors related to positive teamwork experiences [24]. Their findings demonstrate that students learned team management skills, but students also adopted the formal language used in the teamwork literature they read for the course.

This secondary finding by Hirsch and McKenna is part of a larger perspective on teaching reflective practice. Returning to the two types of design knowledge, it is argued that in addition to the language that makes explicit knowledge meaningful, there also must be language to bring the tacit knowledge into clarity [17, 18]. Such language can be made real through the process of reflection and what Mezirow, et al. referred to as reflective discourse [25]. Reflective discourse is dialogue among learners for the purpose of seeking a common understanding. It involves weighing the evidence, maintaining awareness of the context in which meaning is made, reflecting on one's assumptions, and keeping an open mind to alternative perspectives. Reflective discourse can be a way to overlay the language that design researchers have used to understand the design process, with additional language that is contingent on the situated and ill-structured contexts of design.

One tool that can be used to enable reflective discourse on the design process is a visual representation of the design process, or certain aspects of it. Visual representations already play an important role in design, by capturing a designer's current understanding of an engineering problem, providing feedback about strengths and weaknesses of a particular design solution, and communicating ideas and final designs. For example, Cardella and her colleagues demonstrated how student designers create and manipulate sketches to support all aspects of design activity [3]. The role of representations as a reflective tool for design researchers is also well-documented. Our own studies utilized many visual representations of design processes, with *design process timelines* (discussed in the Methodology section) playing key roles [4–6, 26, 27]. Representations have also been used by many other researchers for the study of time allocation in the design process (see [27] for a summary of design process visualizations used in design research).

2.4 Interaction and application

One perspective missing in the previous discussions of PBL and reflective practices is that of engineering students. Student insights about which teaching practices are most engaging may also reflect the activities that are most effective for learning. Their interest in the topics and classroom activities is greatly influenced by the level of engagement or passivity in the learning environment. For those reasons, Pomales-Garcia and Liu [28] conducted a series of focus groups with engineering students to ascertain their perspectives on what entails excellence in education, what teaching approaches work best, and the roles of students and instructors.

The students' responses agreed with many of the practices established as effective teaching. Students emphasized the importance of presenting information in many ways, particularly emphasizing visual displays. Some recognized the value of collaboration and called for its use, particularly in writing papers and giving presentations. When asked how to improve current classroom practices, students called for increased interaction between the students and the instructor. Lectures should be lessened, and greater emphasis placed on solving and discussing problems in class.

The strongest and most consistent response found by Pomales-Garcia and Liu [28] centered on one word: 'examples.' Students were unequivocal in their desire and priority for greater inclusion of real-world examples, problems, and tasks in the classroom. They strongly advocated for more interactive activities wherein the students and the instructors explore real engineering problems. To the students, working with real examples was the crux of excellence in education.

2.5 Bringing research into the classroom

The methods discussed above are important for improving engineering design teaching, but making the link between research and teaching is a highly sought-after and elusive goal [8, 29–31]. Analyzing the citations in recent journal articles and conference papers on design education, Martin et al. [32] found that papers most often cited work from design educators rather than those produced by researchers. Papers on design learning and knowing, design research in general, and education research (e.g., American Educational Reasearch Association) were rarely cited. Moreover, a content analysis of recent papers on design in engineering education journals and conference proceedings conducted by Turns, et al. [30] found that many of the papers were experience reports from their own teaching with varied levels of rigor in evaluating the experiences.

Bringing research findings on design learning into classrooms is an ongoing challenge. Engineering design educators may be unaware of current research findings or lack the experience and skills relevant to interpreting them [8]. Many educational interventions are likely to require adaptation to fit the specific context of an instructor's classroom [8]. Many other features have been found to influence what educators do in their teaching, including (a) available time and resources [33], (b) specific goals they have with their own teaching and challenges that they are facing [34], (c) larger pedagogical frameworks that they bring to their teaching [35], and (d) other demands in their professional life [36]. Even a small classroom activity based on design learning research will need to take these issues into account to promote a smooth and successful adoption by engineering instructors.

3. DESIGN LEARNING: FROM LAB TO CLASSROOM

Over the years, CELT researchers have engaged in the study of how engineers of differing levels of expertise do design [4–6]. We gathered and analyzed data from freshman engineering students, senior engineering students, and practicing engineers on how they worked a common design task. Comparing the performances across experience levels has enabled us to identify specific core design competencies that engineering students can and should learn.

Through publications, presentations, and instructional consultations, we have shared this research with engineering faculty at the University of Washington and several other venues. When our findings were shown to engineering faculty, they agreed that these were major problem areas in students' design work. Subsequently, several of those faculty members invited us to bring some of our research into their classroooms. Collaborating with faculty from materials sciences, aeronautics and astronautics, and mechanical engineering, we developed interactive seminars to improve their students' awareness of the components, complexities, and benefits of well-planned and -executed engineering design processes. These seminars were given as guest presentations by CELT researchers. At the time of this writing, we have given three seminars, two in senior-level capstone courses (with 9 and 22 students) and one in a junior-level project-based course (35 students).

The first seminar we conducted presented multiple aspects of our research and engaged the students in several activities over a 90 minute period. This 90 minute seminar included findings from our research in which we use timeline representations (described in detail below) as well as findings about how context is considered in engineering design processes [2, 37, 38]. Through student feedback and reflection on our part, the seminar has been reduced to 50 minutes with an exclusive focus on the design timelines. In the current seminar format, we present a brief overview of our research and its methodology and then have students analyze design process timelines, a visual representation of our data that has proven to be a powerful analytical tool. By sharing their insights from the timelines, students are exposed to our current research findings and reflect on their own design processes.

4. PAST DESIGN RESEARCH

To describe more fully how we have taken research findings into engineering classrooms through our interactive seminars, we will present the information in a similar sequence to the way it was presented to and engaged with by the students. We will begin in this section with an overview of the research studies we have conducted and explain our data analyses and data representations [4–6]. Then in the following section, we will present the classroom activity and use the students' insights to enter into discussions of the various findings.

4.1 Previous studies: overall description

The primary goal of our research has been to develop an understanding of the effects of experience—both educational and professional—on engineering design processes. Thus, we have studied how beginning engineering students, graduating engineering students, and practicing, experienced engineers do design. Using a verbal protocol method, we asked our participants to think aloud as they designed a playground over three hours in an individually administered laboratory session. The task of designing a playground was specifically chosen to be a topic with which each of our participants would have a general understanding regardless of level of engineering experience. Additionally, we ensured that playground design was outside of any of the experienced engineer's domain expertise.

The design task was completed in a closed room with only a participant and a researcher. The researcher administered the task and answered the participant's questions, which included providing additional information about the playground problem if requested. The researcher also prompted the participant to think aloud if she fell silent for a prolonged period. The participant was given up to three hours to complete the playground design task and could finish early if so desired. All task sessions were audio and video recorded and were later transcribed. Additional details about the design task and study protocols can be found in [4–6].

4.2 Previous studies: participants

Our studies have compared the design thinking and doing typically exhibited by engineers at three experience levels: (a) entering freshmen majoring in engineering, (b) graduating seniors, and (c) experienced practicing professionals. Twenty-six freshmen and 24 seniors participated in the original Atman et al. (1999) study [4]. The freshmen were engineering students who had not yet declared a specific engineering major. Of the 24 seniors, ten majored in civil engineering, seven in mechanical engineering, and seven in industrial engineering. The nineteen practicing engineers in the follow-up study [5] had 7–32 years of experience in their fields and were identified as design experts by their peers. The experts consisted of nine mechanical engineers, three electrical engineers, two civil engineers, two industrial engineers, two systems engineers, and one materials science engineer.

4.3 Previous studies: measurements and analyses

The verbal protocol method provided rich data that allowed for multiple measures and analyses to be conducted [4, 5, 39]. For reasons of space and relevance, we briefly discuss only three analyses in this section: (a) coding the data by design activity, (b) identifying the kinds of information gathered during the design process, and (c) the quality of the completed playground design. Additional methodological details can be found in our previous publications [4–6].

4.3.1 Design activity coding

In our earlier research, we developed a prescriptive model of how design is accomplished by analyzing and synthesizing how design is taught in seven engineering design texts [40]. As detailed

Table 1. Definitions for the design activities and stages. Code abbreviations are in parentheses

Design stages	
Stage	**Activities involved**
Problem Scoping (PS)	Problem Definition, Gathering Information
Designing Alternative Solutions (DAS)	Generating Ideas, Modeling, Feasibility Analysis, Evaluation
Project Realization (PR)	Decision, Communication
Design activities	
Activity	**Definition**
Problem Definition (PD)	Defining the details of the problem
Gathering Information (GATH)	Collecting information needed to solve the problem
Generating Ideas (GEN)	Thinking up potential solutions (or partial solutions)
Modeling (MOD)	Detailing how to build solution or parts of a solution
Feasibility Analysis (FEAS)	Assessing possible or planned solutions (or partial solutions)
Evaluation (EVAL)	Comparing two or more solutions within constraints
Decision (DEC)	Selecting one idea or solution
Communication (COM)	Revealing and explaining design elements to others

in Table 1, the model consists of three design stages that are further broken down into eight design activities. Having been synthesized from multiple models of the design process, we have found this model to be successful at providing a common language for discussing design. Students across engineering disciplines readily recognize and engage with the model's terminology. Furthermore, they recognize that despite its linear presentation, the design activities are iterative and recursive in nature [41].

The definitions of the design activities were used to code the transcripts of the verbal data. Coding began by segmenting each transcript into discrete idea units. Each segment was also timestamped with start and end times derived from the recordings. Taking the segmented transcript, two trained researchers independently assigned a design activity code to each segment. Once finished, the two researchers compared results and arbitrated any discrepancies to agreement. For each transcript, a minimum level of intercoder reliability was required in order to ensure replicability. At the end of the coding process, each participant's design session was segmented into a time series of different design activities (and thereby stages). The timestamps on the segments allowed for quantification of when and how much time was spent in the different activities and stages. The coded data was also represented in several graphical formats, such as the *design process timeline* (see Fig. 1).

4.3.2 *Information gathering*

During the design task, participants could request additional information related to the design problem from the administrator. Available information included budget, information about the site and area, material costs, neighborhood opinions, utilities, and many other categories of information relevant to the playground design problem. These requests were tallied into two types of information requests: (a) requests for information that the administrator was able to answer by giving the participant a slip of information about the topic from the information box; and (b) requests for information that the administrator was unable to answer with a slip from the information box, but were recorded as an information request and later classified by researchers. Each explicit information request (both available and unavailable) was then coded into a list of 17 categories of information [5].

4.3.3 *Quality scoring*

Based on criteria from a guide to playground design [42], each participant's playground design was also assessed for quality [4–6]. The quality score was based on multiple aspects of the design, including: fulfillment of problem constraints; diversity of activities; aesthetics; protection from injury; uniqueness; and technical feasibility. Individual playground components, such as slides or sandboxes, were also assessed for quality if included by the participant. Methodological care was taken to ensure the reliability of the quality scoring as well to ensure compatibility between the student and expert studies (more details can be found in [6]).

4.4 *Previous studies: design process timelines*

In addition to the aforementioned measurements, we developed several graphical representations which allow us to better understand how an individual participant's design process adjusted, shifted, and adapted as it progressed [27]. One of these valuable analysis tools is the *design process timeline,* shown in Fig. 1. In a timeline, time is presented from left to right. For each segment of the transcript, a mark is placed on the line corresponding to how the segment was coded and at the appropriate location given the segment's start time. The width of the mark is proportional to the duration of the segment.

A timeline illustrates when particular activities occur during a design process and may be used to facilitate visual inspection of an individual research participant's design process: not only the activities in which an individual engages, but also the interactions and transitions among design activities over the course of the entire design

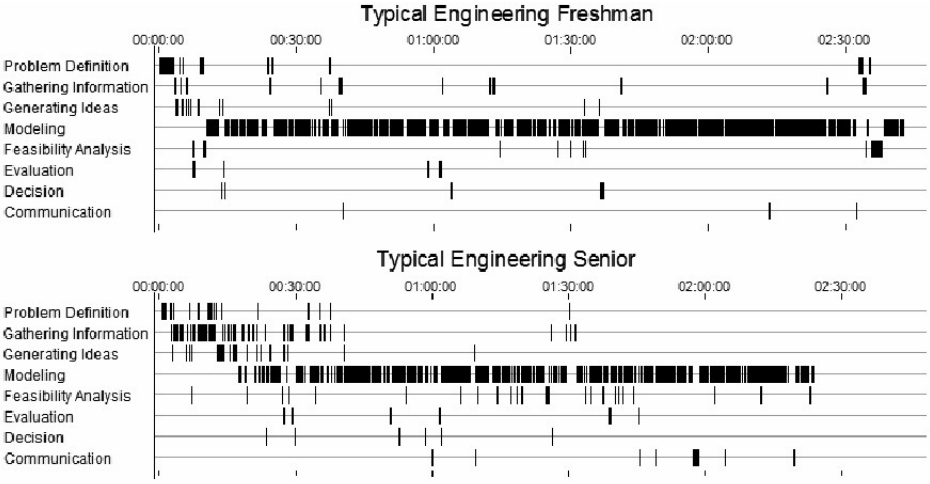
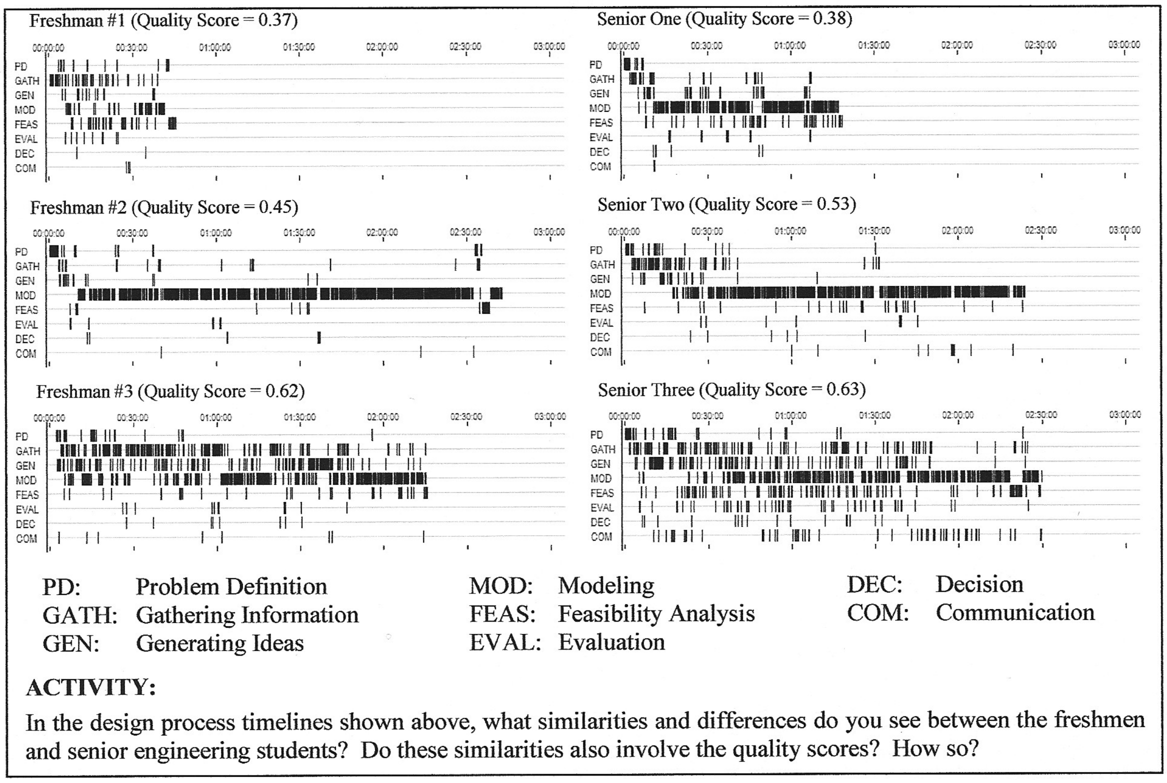


Fig. 1. Design Process Timelines.

process. When juxtaposed, as in Fig. 1, timelines also enable comparative analyses and insight into differences in design processes that can be attributed to the experience levels of the subjects.

5. A SIMPLE CLASSROOM ACTIVITY BASED ON PAST DESIGN RESEARCH

Timelines have proven to be an important means for analyzing design data. Visual inspections of timelines enabled researchers at CELT to distinguish among freshmen and senior students' design approaches and between students' and experts' design approaches. When shown to engineering faculty, they recognized the same patterns of performance, both good and bad, in their students' design work. Hence, the interactive seminar's main activity focused on the timelines by having the students examine a worksheet containing a set of six student timelines and answer the questions posed at the bottom of the worksheet (Fig. 2). Working individually at first and then in small groups, they identified and described in their own words several important design concepts. These insights were then shared with the entire class.



PD:	Problem Definition	MOD:	Modeling	DEC:	Decision
GATH:	Gathering Information	FEAS:	Feasibility Analysis	COM:	Communication
GEN:	Generating Ideas	EVAL:	Evaluation		

ACTIVITY:

In the design process timelines shown above, what similarities and differences do you see between the freshmen and senior engineering students? Do these similarities also involve the quality scores? How so?

Fig. 2. Timeline activity handout. Timelines represent typical low-performing, average-performing, and high-performing freshman and senior engineering students. Timelines originally presented in [4 (reprinted with permission)].

Students' insights often matched findings from our research and they always provided compelling opportunities for classroom discussions. After extensive classroom conversations about the students' insights, the research findings were then presented and discussed for comparison. Additionally, three expert engineer timelines from [6] were presented to and discussed with the students. At the end of the seminar we asked them for feedback on the activity and on lessons learned.

6. STUDENT INSIGHTS FROM CLASSROOM ACTIVITY

During the three interactive seminars, it was evident that students were drawn to the design timelines and became engrossed in their analyses. In each session we asked students to record their anwers to questions on the worksheet handout (Fig. 2). At the end of each session, we also asked students to write down the most important thing they learned during the discussion. We requested that students turn in their worksheets at the end of each session, which resulted in a total of 66 worksheets across the seminars. We later analyzed their insights, looked for common themes, and developed descriptive titles for the most prevalent themes. We utilized a bottom-up approach in our analysis in that we allowed the themes to emerge from the students' insights rather than imposing predetermined categories. The intent of this analysis was to highlight the diversity and astuteness of their insights. In this section, we discuss the nine themes that arose from the data, include illustrative student quotes, and discuss the insights in light of our prior design research findings.

6.1 Student insight: breadth of design activity equates with higher quality design scores

In their analyses of the timelines, most students saw and commented upon the correlation between the quality of a finished design and the completeness, or comprehensiveness, of the process from which it was derived. As this student asserted, '*The people who spent their time on multiple categories generally scored higher*' (*Senior Engineering Student*). This was exactly the kind of understanding their professors were intending for them to develop. Commenting on the breadth or range of design activities was typical, although many students also related the coverage of design activities to academic levels. Several students noted that simply being a more experienced senior student didn't always result in a better design process or a higher score: '*Activity spread correlated better to quality than class standing*' (*Junior Engineering Student*), and '*It is shown that in both seniors and freshmen the more elements that were looked at and discussed the higher the score was*' (*Senior Engineering Student*). When we discussed these insights, we found that the students made the point themselves that being a senior is not a guarantee of a successful design if that student does not pay attention to the completeness of the design process.

Nevertheless, many students did recognize that the seniors' design processes were typically more comprehensive than were the freshmen's. As mentioned earlier in our research, we found that seniors did produce higher quality final designs than the freshmen. However, that finding was not correlated with the overall comprehensiveness of seniors' design processes [4, 26]. This difference, between our research finding and student's insights, became an important point for discussion because it afforded the opportunity to focus on the importance of particular activities within a comprehensive design process. Additionally, we discussed the differences in design quality between freshmen and seniors and introduced them to our expert design quality findings. With 1.0 being the highest possible quality score, the scores by participant group were as follows: freshmen: range 0.19–0.63 (avg. 0.45); seniors: range 0.29–0.70 (avg. 0.51); and experts: 0.43–0.67 (avg. 0.54). As we noted in a previous publication, the quality scores between experts and seniors were not significantly different; however, the expected trend of quality increasing with experience was still present [5]. Students were very attentive to the finding that a few of the seniors were able to achieve quality scores that were similar to those achieved by experts.

6.2 Student insight: seniors accomplish more of design process than freshmen

'*Seniors tend to be more spread out in areas*' (*Junior Engineering Student*). Students often commented on how much more of the design process seniors covered than did the freshmen: '*Freshmen students spend more time on the first half of the process, especially on modeling, while senior students spend more time more evenly on every process*' (*Junior Engineering Student*). Our prior research, however, demonstrated that seniors did not spend significantly more time on the problem overall, but they did tend to transition more often than freshmen among design activities and stages [4, 26]. As with the last student comment, their insights mostly focused on the particular activities that freshmen or seniors were more likely to include or not include in their design processes. With regard to freshmen, typical comments were, '*Freshmen don't spend as much time with the follow-up portion of the design process*' (*Junior Engineering Student*), or '*Generally the freshmen don't do much in the area of evaluation, most time is spent in the theoretical areas, (GATH, GEN, MOD) not in the follow up*' (*Junior Engineering Student*).

6.3 Student insight: seniors do more designing alternative solutions and project realization activities

The 'follow up,' or what several students referred to as the 'second half' or the 'bottom four' design activities were viewed as the real distinction between freshmen and senior design processes. They stated, for example, '*It seems as if the seniors performed more evaluation than the freshmen. The amount of work for each section (gathering, feasibility, etc.) were more spread out over time*' (*Junior Engineering Student*); '*Seniors do more feasibility, evaluation, dec & com. Seniors score higher*' (*Senior Engineering Student*); and '*Senior students appear to have generally more segments of feasibility, evaluation, decision, and communication*' (*Senior Engineering Student*). A few students tried to explain what they were seeing in the timelines in terms of the participants' experience levels, as in the following: '*The freshmen don't have the knowledge for feasibility, evaluation, and decision and thus less time is spent in those areas*' (*Junior Engineering Student*). These students' insights matched our research findings, wherein we found that seniors, indeed, spent more time in the project realization stage (which encompasses the decision and the communication activities) than the freshmen. However, our research also demonstrated that neither group spent very much time in that stage [4, 26] as compared to the experts we studied [5].

6.4 Student insight: more time problem scoping correlates with higher design quality

Students also identified problem definition as a design activity directly linked to design quality. Several students pointed out that this held true for freshmen as well as for seniors, as in the following comments: '*Those who did more planning, gathering of information, etc, received a higher quality score*' (*Senior Engineering Student*), and '*Less time on Problem definition—less score*' (*Senior Engineering Student*). Previous engineering design studies have demonstrated the importance of problem scoping [e.g. 43–45] and its relationship to design expertise and quality design processes. Our own research found that engineering experts tended to spend more time in this phase than students [5]. Although students recognized the importance of problem definition as a general principle, several also observed that seniors were more apt to apply the principle than freshmen.

6.5 Student insight: seniors spend more time scoping the problem

A few students concluded that seniors spent more time than freshmen doing problem scoping activities. For example, '*The freshmen did not plan out the problem in the beginning nor take as long to plan it out as the seniors did*' (*Senior Engineering Student*), and '*Seniors concentration was more spread out and spent more time in the beginning on PD and GATH before starting to model. Similarly, the more spread out the concentrations was, the better quality*' (*Senior Engineering Student*). These insights, although not supported by our research, nonetheless provided an opening for us to discuss the value of problem scoping, which is strongly suggested by our and others' research.

In our research, we found that seniors did not spend more time in problem scoping activities than the freshmen. Seniors did, however, acquire more information in more categories, such as budget and safety guidelines for play equipment, than the freshmen. We also pointed out that seniors still covered less than half the categories of information available, and seniors gathered significantly less information than our experts [5]. Information gathering was recognized by students as a significant activity, as the next section shows.

6.6 Student insight: time spent gathering information equates to design quality

'*Students with higher quality scores do a lot more gathering*' (*Junior Engineering Student*). '*Lower quality designs spent very little time gathering information*' (*Senior Engineering Student*). As did these students, some students framed this insight as a general statement that was not necessarily linked to academic level. However, just as many students linked seniors with increased information gathering. For instance, '*Seniors spent more time in GATH—seniors QS [quality scores] higher*' (*Senior Engineering Student*), and '*A lot of varieties in the information gathering step— all proceed at the beginning but some (mostly seniors) would gather info along the process*' (*Senior Engineering Student*).

Students were correct with this insight. In our studies comparing freshmen and seniors, we found several significant differences related to their information gathering practices. For example, the total number of information requests and the range of information categories covered were larger for seniors. Additionally, the number of information requests correlated with higher quality solutions [4, 46].

6.7 Student insight: everyone spends most design time in modeling

'*Modeling was commonly the most common activity*' (*Senior Engineering Student*). '*Modeling seems to be the dominant characteristic among freshmen and seniors*' (*Junior Engineering Student*). '*All persons spent much of their time in modeling*' (*Senior Engineering Student*). These student insights were far from surprising. The timelines display that modeling is the primary design activity of most designers in the sample. This holds true for freshmen, seniors, and experts. The average percentages of design time used in the modeling activity were 55.8% for freshmen, 57.3% for seniors, and 55.1% for experts [5]. Although easily discerned from the timelines, these insights were nonetheless valuable topics for our discussions. Significantly, although students linked several design process activities to design quality, they recognized that modeling—the activity which consumed most design time—was (to some extent) inversely correlated with quality. In effect, the more modeling appeared as a contin-

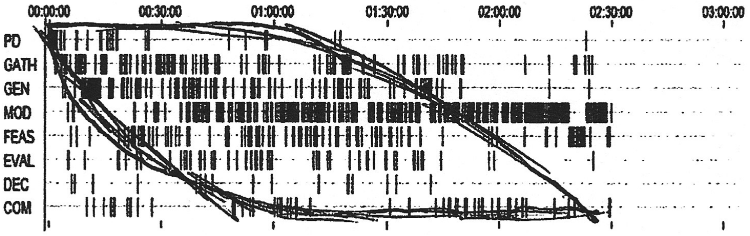


Fig. 3. Scan of student's 'Ideal Project Envelope'

uous activity on the timelines, the less time was then available for other important activities. Students offered conclusions such as, '*Spend more time on problem definition and gathering information before jump to modeling*' (*Senior Engineering Student*) and '*Avoid getting stuck in the modeling phase. Continually gather information & check to be sure you are working to make your goals*' (*Senior Engineering Student*).

6.8 Student insight: iteration is tied to design quality

A few students concluded that simply by virtue of being a messy looking process, a higher quality design was achieved. As stated by this student, '*Jumping from task to task—higher q [quality] score*' (*Senior Engineering Student).* This observation may not have been that far from the mark. In her study exploring iterative design behavior, Adams (2001) found that a designer's understanding of a problem or possible solutions evolves through a process of iteration. Analyzing iterative activity in engineering design across levels of performance and experience [41], she observed how designers continually revisit and reflect on each aspect of a design task. One of Adam's most interesting findings was that seniors not only spend more time iterating, but also spend more time engaged in 'coupled' iterations in which the *problem definition* and *solution* co-evolve. The following student insights fit well with those findings: '*Those who constantly looked back to gather info, put it together, then made sure to properly evaluate it got much higher quality scores*' (*Senior Engineering Student*); '*More dynamic interplay between modeling and secondary processes for seniors, lots of back and forth*' (*Junior Engineering Student*); and '*Seniors checked FEAS & EVAL more throughout—seniors QS [quality scores] higher*' (*Senior Engineering Student*).

6.9 Student insight: a good design process has a shape

One surprising insight, articulated by only a single student, was the notion that a design process has a shape. The student defined the shape as the 'Ideal Project Envelope,' and drew a shape over the Senior Three timeline (see Fig. 3).

This insight closely fits with a familiar design process pattern previously identified in our research—the *cascade pattern* [5, 47]. This pattern was described as a *cascade* through the design activities over the time spent designing. A significant portion of time at the start of the design process is spent in *problem scoping,* which then gradually shifts into a more concentrated focus on *developing alternative solutions*. Some transitions back into *problem scoping* occur throughout the process as well as transitions into *project realization*. This pattern was often identified in the experts' timelines (14/19), less common among the seniors (9/24), and rare among the freshmen timelines (4/26).

We would not have expected this student to describe the ideal project envelope in the same way we described the cascade pattern, however the concepts themselves seem very much in line. Rather than conceiving of the design process as a formalized progression (e.g. linear, stepped, staged, or phased) this student simply described a process that had a primary direction of movement, encompassed every activity, and provided lots of room for iteration.

7. DISCUSSION

While in the midst of the student seminars, as we were discussing and comparing their insights and our research findings, it became clearly evident that we had achieved at least part of our goal, which was to increase the students' awareness of important aspects of design.

7.1 Factors for success

Students in the seminars were deeply engaged in the class exercises and were not only able to grasp important concepts and lessons, but also were able to reflect on their own design processes in relation to the timelines they had examined. The class exercises were successful because they modelled an inductive learning process in which students reflected on prior knowledge, became interested and motivated to learn, and were provided information as the need arose.

7.1.1 Using an inductive process

It would have been fairly straightforward to have first presented some of our important findings and then used the timelines to illustrate the points we were making. That is the standard approach, or what Prince and Felder [14] described as the deductive model, wherein 'Little or no attention is initially paid to the question of *why* any of that is being done . . . why should the students care about any of it (p. 123)?' By asking students to examine the design timelines without benefit of the researchers' opinions we were in effect allowing them to determine *why* it mattered. When asked to sum up the most important thing they learned, students provided answers to the *why* question. Here are a few of their answers: '*Success is strongly correlated with gathering data and defining the problem early on*' (*Senior Engineering Student*); and '*Problem definition is key to the overall project. Remind yourself of what you are doing and what is really being asked. Pick your head up from the paper (modeling!) and analyze the problem*' (*Senior Engineering Student*); and '*The more inclusive the design process is, the better the outcome is*' (*Senior Engineering Student*).

7.1.2 Connecting with students' prior knowledge

Asking students to describe in their own words what they were seeing in the timelines caused them to search their memories for what they already knew about design. In that process, they also had to link the new information to their existing knowledge. This cognitive process enables long term memory and more transferability of their new insights back into their design project activities [14].

7.1.3 Providing just in time information

One of the hallmarks of PBL is to wait until students develop a need for more information before it is provided [12, 14]. We worked with each of the professors to determine an opportune time to conduct the seminars. In each case, students were already engaged in their project teams and in the design process. Those activities enabled them to quickly perceive the relevance of the timelines to what they were doing. As one junior engineering student wrote, '*I think this can help us with our project a lot. Thanks a lot for this.*'

7.1.4 Fostering reflection and metacognition

As was discussed earlier, students can learn a lot from engagement in design projects, and becoming more metacognitive is considered one of the primary benefits [17, 18]. It was evident from their insights that they were developing detailed conceptions of design processes. Those conceptions enable comparisons with their own design activities. Additionally, several students recognized the value of metacognition from the timelines. As this senior proposed, '*Also, the iterative, checking the process throughout the process, the better the end result is.*'

7.1.5 Engaging student interests

The seminar and timeline activity also integrated several of the elements that students noted as effective engineering teaching practices in Pomales-Garcia and Liu's study [28]. The timelines provided real examples of engineering design processes for the students to dissect and discuss. The ensuing interactive discussions further linked the seminar material to their engineering educations.

7.2 Next steps

As we alluded above, we believe the seminars were only partially successful. We know that by the end of each seminar, students had learned important lessons about design processes. What we do not know, however, is whether they later demonstrated that knowledge in their design teams. As one senior student suggested, '[I] *suggest [capstone course] students to keep daily logs similar to timelines shown. May help us realize if we are stuck in a certain activity.*' We think this is a good suggestion and have developed a set of individual and team design process logs that students could use to reflect on and monitor their design processes, and could potentially be useful for assessment purposes. One of our next steps will be to test the logs in the classroom.

So far, we have conducted seminars in three engineering disciplines, and plan to collaborate with instructors in other fields to plan similar seminars that focus on using timelines and our research findings to highlight important aspects of engineering design processes. We also plan to develop classroom activities that focus on other aspects of our research, such as the kinds of information gathered while completing a design task, and how that information may inform the scoping of a design problem [2, 22, 46]. For example, we recently used an activity in a freshmen seminar that had been used as a research task in the Academic Pathways Study (APS) [2, 38]. In this activity, referred to as the Midwest Floods Design Task, students are asked to list the kinds of information they think is important for designing a retaining wall on the Mississippi river. We used this task in the freshmen seminar to introduce students to the wide range of issues (e.g., technical, economic, environmental, and social) that engineering designers must consider. The students not only enjoyed the opportunity to think like an engineer, but they also liked comparing their own ideas to some of the findings from the APS.

Additionally, we are envisioning ways to make our timelines and seminar materials more widely available to engineering educators. We have introduced our design research to colleagues at several conferences and we have heard back from them that they are already using, or they are planning classroom activities that include our findings and timelines. We hope to eventually house our design research materials and classroom activities on the web. Until then, we will provide them to educators who contact us directly.

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