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Self-Evaluation of Design Decision-Making Skills Gained through Student Generated Learning Aids

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Abstract

This paper presents the findings from research in improving undergraduate engineering design decision-making skills. This work is motivated by the need to provide students with more design-decision making experience to enable them to be ready to engineer upon graduation. In this research, third and fourth year undergraduate mechanical engineering students were guided through the process of designing learning aid prototypes to be used in general engineering education. Students were encouraged to use advanced technologies such as 3D printing and virtual simulation to realize their concepts. This project assisted students in identifying their own and typical misconceptions and devise tools which corrected those cognitive errors. A series of self-evaluation methods were used to identify the student's perception of their decision-making skill levels. Over the multiple categories of design decision-making skills examined, there were various levels of change in the student's perceived skill level. These results identify some of the challenges in using perceived skills assessment as a means for evaluating education reform efficacy. Inconsistencies between student reporting improvements in categories but also reporting reduced skill levels indicate that students may grow in their understanding of their own skill limitations through the project activities. Overall, this work demonstrates a situated cognitive approach to teaching design decision-making in an authentic environment and presents metrics for evaluating the efficacy of that approach in terms of perception. The objective of this work is to enable graduating students to be confident in their abilities to make design decisions in an industrial setting at the beginning of their careers.

Introduction

It is clear from engineering education research that no single style of teaching or learning can be effective considering the diverse quality and background of engineering students[1]. Engineering educators find the use of physical and virtual learning aids especially effective for conveying concepts by providing the hands-on aspect desired by many students. Case-based reasoning[2] and educational pedagogies of situated cognition[3-5] support providing students with concrete examples of fundamental concepts. Further, this field includes multiple research efforts regarding the efficacy and best practices of teaching aids and their use in curriculum. However, even with effective learning aids, engineering education struggles to convey both a depth of information as well as the skills needed to apply that knowledge.

A gap in recent graduate's ability to apply their knowledge in an industrial setting has led to approaches which integrate more project-based learning[6]. Specifically, graduates lack decision-making skills[7] and skills related to working in open and collaborative settings[8]. Graduates usually have very little experience working in open-ended projects and understanding exactly what sets of decisions need to be reached to achieve a final engineering design. The missing skill sets can broadly be described as: 1) Making effective design decisions to select between alternatives to satisfy multiple and sometime conflicting requirements, and 2) Following a systematic approach such that those decision and their effect on the final design can be communicated. This has been summarized by some employers as "lacking the feel" for engineering. The motivation for this work is that by providing opportunities to develop these skills, students will be better prepared for their engineering careers.

While innovative methods for providing students with those skills is the central focus of this research. Evaluation of the effectiveness of those skills is critical for furthering this research and providing metrics and goals for future curriculum changes. Therefore, in this paper we present findings from a novel approach to teaching fundamental design decision-making by enabling students to become creative partners in their education. The educational research being explored is the application of situated cognition and cognitive apprenticeships. The assessment methods include skill division as assessment and comparison of individual self-evaluation and external expert evaluation of the growth in those skills.

Theoretical Framework

Early engineering education research focused on curriculum-related topics, such as concepts and principles; learning strategies and learning styles; human development; problem solving; design; and assessment and evaluation[9]. During the 1960s through 1980s, engineering education concentrated on methods of classroom instruction. Between 1980 and 2000, they reached a higher level of scholarship maturity, yet kept their focus on curriculum and methods[10,11]. Since that point, there has been an emerging interest in the integration of educational psychology and cognitive science theories into engineering education. For example, the theory of situated cognition has been explored in the context of industrially situated virtual laboratories[12] and STEM integration in the precollege engineering classroom[13,14].

Situated cognition happens in a contextualized, real-world setting where the learner is directly interacting with other learners while learning important content. This is crucial in the discipline of engineering design, as students need to grasp important design principles but are often removed from the actual environment where they will apply these principles. Learner reflection while present in the authentic environment is also a crucial part of this approach[3]. Learners gain knowledge and skills through practical, hands-on experience rather than in a classroom viewing a lecture or presentation. Being in an authentic setting allows learners to apply specific engineering design content knowledge acquired in a traditional orientation or training session. An important aspect of situated cognition is the cognitive apprenticeship, in which learners acquire, develop, and use cognitive tools while participating in an authentic activity[3]. Through a cognitive apprenticeship, learners directly observe what happens in engineering design, model the practice of their teacher, and reflect on the ideas they learn, including addressing any related misconceptions. Teachers encourage the development of their learners by making tacit knowledge explicit, modeling effective strategies for completing tasks, providing scaffolded support when learners are practicing new tasks, and offering specific feedback for improvement[15]. This apprenticeship is vitally important for the transferability of what is assumed to be learned in an orientation or training session to become actual practice.

As part of this research, additive manufacturing is being explored as a means of implementing the theoretical cognitive learning concepts. Research on the use of additive manufacturing (3D printing) in teacher education has shown increased interest among preservice elementary teachers when teaching mathematics[16] and more customized methods for elementary mathematics and science pedagogy[17]. As related hardware and software have become more affordable and user friendly, these printing technologies have recently found their way into the K–12 classroom setting to facilitate the creation of physical objects for hands-on discovery learning[18]. Existing research has suggested that activities involving related 2D digital fabrication technology can inspire K–12 student creativity[18-20] increase mathematical content knowledge[21,22], and positively affect attitudes toward STEM subjects and careers[23].

In fact, the use of 3D printing for creating customized learning aids by and for education professionals is growing increasingly common. 3D printing has been used to create customized, 3D elevation maps and models of biological structures, asteroids and planetary landscapes in Geoscience undergraduate classrooms[24] and as a resource in libraries[25] to facilitate faculty and students' data visualization techniques. Additive manufacturing has been used in chemical engineering education to generate plastic models of molecular potential energy surfaces useful for understanding molecular structure and reactivity[26].

Finally, the critical area of decision making in engineering has been highlighted by many as a growing need. For example, Purzer and Chen[27] reviewed numerous first year textbooks and education research papers to identify the fundamental approaches to providing decision making skills. Further, and specifically for design-related decision making, Mourtos[28] develops categories of skills of design and presents some methods of assessment. Numerous methods for addressing the lack of design skills observed in undergraduate students have been proposed[7,29-32]. For example, Dym et al.[33] present an overview of project-based learning as a method to address these skills Finally, any method presented will include the assessment of the growth of those skills such as the survey tool from Gentili et al.[34]. These latter authors categorize the skills learned in context of engineering design as:

1. Working effectively in teams
2. Gathering supporting information
3. Defining the specific problem
4. Idea Generation
5. Evaluation of concepts and making decisions
6. Implementing a selected concept
7. Communicating the design effort

These skill categories encompass the activities of engineering design but do not address the fundamental cognitive model students need to follow to achieve successful designs. In this work, we use these categories to define the practical skill sets for self-assessment. With respect to ethical decision making, Zhu et al. explored several tools and developed a hybrid (quantitative and qualitative) tool for assessing those skills[35]. In this work we are less interested in identify the "correct" assessment method but rather in exploring the consistency and overlap between self-assessment of skills and mentor provided evaluations.

Quasi-objective methods of evaluating design skills have been developed and provide a rational basis for assessing student's performance[28]. Further, within the context of the cognitive apprenticeship model, the instructor is a valid expert to perform this evaluation. However, the focus of this work is in the perception of design skill both from the student's perspectives and from the experts who interact with them. From a broader perspective, the objective assessment and the subjective perception are both needed to address the concern of graduate unpreparedness.

Data Sources

The data supporting this research was gathered over the course of a 16 week semester in a mechanical engineering design course. There were 82 junior and senior undergraduate students enrolled in this course. These students formed 21 self-selected groups consisting mostly of four members each with a few three-member groups. Student groups worked with faculty members and one graduate student who all have responsibilities of teaching courses in the mechanical engineering curriculum.

Methodology

In the following sections we detail the novel approach to teaching engineering design decision making skills and the assessment methods used for evaluating those skills. In order to understand the effectiveness of the project in terms of the skill organization and assessment tool, it is important to present the actual project that was implemented. The following sections are those the steps of implementing a curriculum change.

Establishing an authentic learning environment

For this study, the student groups were tasked with identifying a challenging engineering concept and to create a device which could effectively demonstrate that concept. To make this an authentic learning activity, students were tasked with identifying an instructor who currently or recently has taught a class where their learning aids could be used. This instructor becomes a potential client and the group of students becomes a small design firm attempting to identify and meet their client's needs. It is typical that students do not have a clear concept of what topic should be addressed. The clients helps focus their initial concepts towards a useful learning aid.

To motivate the teams to produce their best work, the learning aids that were liked most by their clients and seemed possible to create in the second half of the semester were allowed to be manufactured. Since some groups chose to demonstrate the same engineering concept this led to a natural competition between groups as would be typical in real world design work.

Implementing the cognitive apprenticeship

Following the paradigm of situated cognition and specifically the cognitive apprenticeship model, students were provided a series of weekly deliverables to guide them through making appropriate design decisions. This process relied on traditional engineering design process and tools. Specifically, student groups were required to create and submit:

1. A list of customer requirements and preferences with order indicated for preferences if possible.
2. Three well developed concepts generated by synthesizing a variety of concepts following their choice of ideation method.
3. A functional model of a single concept selected by using a systematic method of ranking concepts against customer requirements and preferences.
4. Documentation of using machine component standards to identify appropriate rough sizing of components.
5. A summary document that serves as a detailed sales pitch for the perspective client.
6. A physical prototype which describes the function of the device.

Students were encouraged but not required to use the 3D printer for creating their final physical prototypes.

Creating a feedback structure with reasonable restrictions on client's time and resources

In order to manage the design progress of the 21 different groups and the additional time constraint imposed on the instructor-clients, a set of reasonable restrictions and distributed feedback was created. Two undergraduate teaching assistants provided feedback to student groups on each of the deliverables. Groups were not permitted to meet with their clients more than twice at the beginning of the project and once at the end of the design stage. These meetings were requested to be no longer than 15 minutes. However, many of the instructor-clients were eager to spend much more time with the student groups.The mechanical engineering department provided the 3D printing resources. To enable sustainable usage, groups were asked to limit printing to six cubic inches of ABS plastic model material. No limits were given for the support material, which is also required when using these particular 3D printers.

Results

Student Survey Results

All students participating in the course were given a design decision-making skill assessment survey at the beginning and at the end of the course. For the seven categories identified as fundamental aspects of design decision-making skills, 30 supporting skills were identified following the assessment approach of [34]. Students were asked to rank themselves from novice to expert (with 5 discrete levels overall) for each of the 30 skills. At the end of the course, students were again asked to rate their skills in those exact 30 categories. Additionally, students were asked to rank their agreement with statements indicating that they improved their skills in the seven high-level categories. The intent of these additional questions was to identify if improvement in the 30 lower-level skills was connected to improvement in their associated high-level skill.

To evaluate improvement in self-reported skill, the numeric difference between the post course survey and the initial course survey for the 30 low-level skills was calculated. Note, that this assumes that the difference between skill levels can be treated as equal. The impact of this assumption will be addressed in more detail below. Finally, the change in the 30 low-level skills was evaluated and compared to the student's self-reported growth in the seven high-level categories. In total, 55 students agreed to allow their survey data to be used for research and also completed both surveys.

Table 1 describes the averages and significant changes in skill levels based on a single tail T test at 95% confidence. As the table shows only 3 skills did not show significant growth (Skills 1, 8, and 21). Table 2 shows that a majority of the students also reported growth in each of the 7 high-level skill categories.

To evaluate the underlying framework proposed in this work of subdividing the seven high-level skills into 30 lower-level skills, we assessed both the correlation of evaluated growth and self-reported growth and the skill specific tendencies. Each of the 7 high-level skills was compared to each of the 30 low-level skills using a Spearman rank correlation analysis. No significant correlation was found between the change in any low-level skill and the reported improvement in any of the 7 high-level categories. The assumption that the difference between skill levels is equal may have contributed to this finding. To adjust for this, the evaluation of improvement was simplified to simply represent increase, decrease, or no change in skill. These per-skill improvements were compared within each group. That is, the set of 17 students who strongly agreed that this course improved their design decision making skills were compared to identify which specific sublevel skills improved. If the area of open-ended problem solving is accurately subdivided than it should be expected that there would be a correlation in each of these groups with those questions. For many categories a high level of correlation was found within these subset groups. However, there was also correlation with numerous other questions as well. Thus, this approach is ineffective for identifying if improvement in those particular sub-level skills improve the high-level skill. Moreover, it was common to find that student who reported minimal improvement in high-level skill also reported minimal improvement in numerous sub-level skills. This may indicate that the student's personal experience in the class largely effected the second survey results.

Table 1. Skill questions by category and relative improvement reported.

Skill	Question	Mean	STD	T Statistic
	Working in Teams			**T-Sig = 2.005**
1	Participating effectively in groups or teams.	0.091	1.005	0.671
2	Understanding my own and other member's styles of thinking and how they affect teamwork.	0.655	0.985	4.926
3	Understanding the different roles included in effective teamwork and responsibilities of each role.	0.364	0.988	2.729
4	Using effective group communication skills: listening, speaking, visual communication.	0.364	0.950	2.839
5	Cooperating to support effective teamwork.	0.291	0.896	2.408
	Gathering Supporting Information			
6	Gathering information, use various sources and techniques, and analyze their validity and appropriateness.	0.527	0.790	4.949
7	Using important visual and oral techniques (questioning, observing) for information gathering.	0.691	0.998	5.136
8	Using library resources effectively in accessing relevant information.	0.127	1.123	0.840
	Problem Definition			
9	Defining problems, which includes specific goal statement, criteria and constraints.	0.691	0.900	5.693
10	Understanding what is open-ended and what is defined in problems.	0.600	1.116	3.989
11	Developing specific goal statements after gathering information about a problem (need).	0.909	1.127	5.984
12	Recognizing the importance of problem definition for development of an appropriate design.	0.800	1.238	4.791
13	Developing problem definitions with specific criteria and constraints.	0.709	1.117	4.709
	Idea Generation			
14	Utilizing effective techniques for idea generation.	0.745	0.985	5.610
15	Identifying and utilizing environments that support idea generation.	0.673	0.963	5.179
16	Brainstorm effectively in teams.	0.273	0.952	2.125
17	Using techniques that synthesize ideas to increase overall idea generation.	1.000	1.000	7.416
	Evaluating Concepts			
18	Utilizing critical evaluation and decision making skills and techniques, including testing.	0.782	0.994	5.832
19	Following an iterative approach that employs evaluation repeatedly in their design process.	0.818	1.188	5.109
	Implementing Concept			
20	Implementing a design to a state of usefulness to prospective clientele.	0.945	1.208	5.803
21	Managing time and other resources as required to complete their project.	0.109	0.936	0.864
22	Following instructions provided by others in implementation.	0.436	0.788	4.107
	Communicating Design Effort			
23	Communicating with team members at all stages of development and implementation of design solutions.	0.436	0.938	3.449
24	Practicing effective listening skills for receiving information accurately.	0.382	0.782	3.623
25	Exhibiting appropriate nonverbal mannerisms (e.g., eye contact) in interpersonal communication.	0.345	0.966	2.651
26	Giving and receiving constructive criticism and suggestions.	0.564	0.764	5.471
27	Recording group activities and outcomes, ideas, date, etc. in personal design journals.	0.582	1.031	4.186
28	Producing technical papers and memos in acceptable style and format.	0.564	1.085	3.854
29	Presenting design information in group oral presentations.	0.818	0.945	6.424
30	Communicating geometric relationships using drawings and sketches.	0.582	1.049	4.115

Table 2. High-level improvement reported by category.

	High Level Skill Assessment Question	Strongly Agree	Agree	Neither	Disagree	Strongly Disagree	No Answer
1	By taking this course I improved skills in: Working successfully in a team environment.	24	26	4	0	1	0
2	By taking this course I improved skills in: Effectively gathering information to solve design problems.	20	26	6	1	2	0
3	By Taking this course I have improved in my skills of: Defining open-ended problems.	17	32	3	3	0	0
4	By taking this course I have improved in my skills of: Generating/brainstorming concepts.	15	33	4	1	2	0
5	By taking this course I have improved in my skills in evaluating and making a decision between alternatives.	13	36	2	2	2	0
6	By taking this course I improved my skills in: physically implementing a design concept.	17	28	5	3	1	1
7	By taking this course I have improved my skills in communicating project work.	16	33	3	2	0	1

Student and Client Perspective of Learning Aid Outcomes

At the completion of the eight week design phase, students were directed to meet with their clients to present their prototype for evaluation. Students were asked to individually complete a survey describing the outcome of this meeting. The first question was if they were able to meet with their client. The second question asked for the student's perception of their client's interest in the prototype produced. Finally, the students were asked to list what the clients liked and did not like about the prototype. 65 students completed the study so some groups were represented by more than one response. This was a desired outcome as not every student may have the same perception of the meeting. 95% of students reported being able to meet with their client. A Likert scale was used for the student to gauge their client's interest in the prototype. They reported: 36.9% Very Satisfied, 41.5% Satisfied, 20% Not Satisfied or Dissatisfied, 0% Dissatisfied, 1.5% Very Dissatisfied.

Finally, at the end of the semester the faculty who acted as potential clients for the student's learning aids were asked to identify the impact of the activity and the 3D printers for each team. 10 faculty members served as potential clients for the 21 groups. The number of groups that each faculty member met with varied from one to four. Seven faculty members provided survey responses covering a total of 16 groups. On average, a faculty member met with groups three times during the semester. Groups were instructed to meet with the clients at the beginning and the end but many groups needed clarification of their client's preferences and met with the client additional times. The average time a client spent with the group was 15.8 minutes. A summary of the client's perspective can be seen in Tables 3-4. Two groups did not present their prototype learning aid to the client and so the client was unable to address questions regarding those groups.

TABLE 3. Client's perspective of the prototypes generated.

How satisfied were you with the prototype generated at the end of the 9th week?	
Possible Response:	*Total Responses:*
Very Satisfied	3
Satisfied	5
Neither Satisfied or Dissatisfied	3
Dissatisfied	0
Very Dissatisfied	0
Cannot Rate	2

TABLE 4. Client's perspective on the growth of the group's conceptual understanding.

The group's understanding of the concept the learning aid demonstrated was deeper as a result of creating the learning aid prototype.	
Strongly Agree	4
Agree	3
Neither Agree nor Disagree	2
Disagree	0
Strongly Disagree	0
Cannot Rate	2

Conclusions

In this work we explored how to assess the perception of design decision-making skill improvement when implementing novel methods of teaching. Specifically, an application of the cognitive apprenticeship learning framework was used to develop a project where students generate products in realistic environments for actual clients. In order to assess improvement in learning skills a distinction of those skills was developed and a survey tool used to assess perceptions of pre and post course expertise levels. Seven high-level skills were subdivided into 30 supporting skills. For each of the 30 skills students rated their level of expertise at the beginning and the end of the course. Further, at the end of the course they were asked if they agreed or disagreed on a Likert scale that the project improved their skills in each of the 7 high-level areas. Finally, the clients also evaluated the students design skills and provided their perception of the students' growth in learning.

The underlying approach in this work is that objective evaluation of design decision-making skills is incredibly difficult on an individual level and effectively impossible with typical large undergraduate classes. Therefore, we wanted to explore the idea of self-evaluation of skills and determine the internal and external consistency of those evaluations. Results from these assessments showed that students did show improvement in many supporting skills and these were consistent within groups that reported that the projects improved their design skills. However, numerous students reported a lower-level of skill at the end of the course for some supporting skills. This seems to stem from two groups. From the groups that reported high-level improvement in skills we theorize that these students may have begun with an unrealistic evaluation of their own skill level at the beginning of the course. Another set of students reported no high-level skill improvement in the course. These students who also showed a decrease in supporting skill may have been expressing frustration with some aspect of the course in general. Finally, the supporting skills could not be correlated with their high-level classification. We believe this is due to the significant amount of overlap between skills and activities that affected those skills.

In future work we will explore reducing these confounding elements by requesting a qualitative response for students who report improvement and decrease in skill level at the end of the project. These responses should identify which aspects of the project are most effective at improving specific supporting skills and validate the category specification. Further, we plan to explore how the perception of growth in design skills can be connected with methods that attempt objective skill assessment to provide a holistic perspective.

Ultimately, the aim of this work is to equip engineers with skills to design upon graduation with confidence. By developing approaches based on scientifically validated methods of learning and thorough holistic evaluation metrics we can support continued industrial innovation.

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