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# Centralized Generative Design Activities to Enable Design throughout the Engineering Curriculum*

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This paper describes a paradigm of engineering education to implement design activities throughout the engineering curriculum. Traditionally, engineering design is taught through a capstone experience where students implement the concepts learned in technical courses. There is growing interest in changing this paradigm to teach the technical concepts through the hands-on activity of design. However, there are significant challenges to implementing this paradigm. These include time, coordination, and expertise limitations. This paper describes a paradigm where design is centralized to a specific course activity while the design artifacts are learning aids that support the other technical courses and correct misconceptions of concepts presented in those courses. We conducted a preliminary study in a 16-week design course for 89 junior and senior undergraduates in mechanical engineering. Results indicate the approach both improves the design decision-making skills of students and provides a workable framework to implement design throughout an engineering curriculum.

**Keywords:** design education; situated cognition; cognitive apprenticeships

## 1. Introduction

The use of a variety of educational styles and techniques to effectively engage a diverse set of students is commonplace in engineering education [1]. Specifically, engineering educators find the use of physical and virtual learning aids especially effective for conveying concepts. Case Based reasoning [2] and 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 [6–8]. However, even with effective learning aids and practices, engineering education struggles to convey both a depth of information as well as the skills needed to apply that knowledge.

A gap in recent graduates' ability to apply their knowledge in an industrial setting has led to approaches to integrate more project-based learning [9]. Specifically, graduates lack decision-making skills [10] and skills related to working in open and collaborative settings [11]. Graduates usually have very little experience working in open-ended projects and understanding exactly what decisions need to be reached to achieve a final engineering design [9, 10, 14–16]. The missing skill sets can broadly be described as: 1) Making effective design decisions to select between alternatives to satisfy multiple and sometimes conflicting requirements, and 2) Following a systematic approach and then recording and communicating decisions to understand the effect of those decisions on a final design. This has been summarized by some employers as "lacking the feel" for engineering. Most researchers contextualize the issue as finding the balance between engineering science and engineering application [11, 17, 18]. Numerous efforts at improving engineering education by integrating design activities have been pursued to improve the engineering readiness of students [12, 13]. Engineering design throughout the curriculum is often cited as a method of providing students with the application skills missing when only engineering science is covered [19, 20]. More recently, engineering education researchers have looked to learning research to identify scientifically validated approaches for meeting this need [21, 22]. Specifically, the theory of situated cognition is a potential model for engineering education reform [21].

This work presented in this paper builds on the use of situated cognition theory with a focus on addressing a specific gap in graduates' skills, namely design decision-making. The field of engineering design theory and methodology contains a rich exploration of how engineers design [23]. Decision-based design is one theoretical construct, which describes the process of conceiving and developing engineered solutions as a series of decisions [24]. Motivated by this perspective, the authors believe the perceived lack of readiness of engineer-

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ing graduates is largely due to a lack of design-decision making skills.

Therefore, in this work we have identified specific skill sets related to making design decisions in an engineering context. We base these skills on the categories identified by Gentili et al. [25]. Further, through the implementation of a design activity based in situated cognition theory, we believe that these design skills can be measurably improved, specifically through the cognitive apprenticeship. A cognitive apprenticeship involves the process where someone who has mastered a skill teaches that skill to a novice [26]. We utilize this approach to develop a novel curriculum model where students conceive, design, and build educational learning aids for their own courses. The aim of this activity is to provide an example design activity that can be implemented in various courses in the engineering curriculum. This is a new model of how to implement the goal of having "design throughout the curriculum."

In the following sections we present the theoretical foundations for this work with respect to engineering design decision-making and the learning theory of situated cognition. Following this, we present the specific educational intervention built on this foundation and the data gathered during that activity. The results of the intervention and potential impacts on engineering education are discussed in the conclusion.

## 2. Background

### *2.1 Engineering design and decision-making*

Engineering design theory is a relatively modern science studying the activity of design [23]. A prominent theory based on the mathematics of optimization is called Decision-Based Design (DBD) [24, 27–30]. In DBD, the fundamental activity of design is the cognitive process of decision-making. Both descriptive and prescriptive models of how engineers make or ought to make decisions have been developed [31, 32]. The cognitive focus of this branch of design theory clearly overlaps with recent work in understanding the cognitive process of learning in engineering education [21]. In this work, we are identifying a potential bridge between the cognitive research in DBD and cognitive theories found in the learning sciences, specifically situated cognition.

### *2.2 Situated cognition learning theory*

Situated cognition happens in a contextualized, real-world setting where the learner is directly interacting with other learners while understanding 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 an important 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, which assists learning by helping learners to 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 identify 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 [26]. The student in this context must observe how the professor applies engineering design principles and experiment with the same methods. Through the cognitive apprenticeship, the student must confront his or her beliefs about the role of the engineer in his specific context and decide how and when to apply the instruction.

### *2.3 Measuring design skills*

Numerous methods for addressing the lack of design skills observed in undergraduate students have been proposed [10, 19, 33–35]. For example, Dym et al. [36] present an overview of project-based learning as a method for providing these skills. Any method presented will include the assessment of the growth of those skills such as the survey tool from Gentili et al. [25]. These latter authors categorize the skills learned in the 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 define the design decision-making activities within these categories to identify the practical skill sets for assessment.

In summary, this work is built on the theoretical foundations of understanding design as a decision-making process and situated cognition to develop a novel education intervention for the engineering curriculum.

## 3. Educational intervention and experimental method

### *3.1 The centralized generative design paradigm*

We developed an education intervention in the mechanical engineering curriculum. In the study discussed below, engineering students in a junior level design course developed hands-on learning aids, which could be used in their engineering curriculum. The instructor for the design course served as the mentor for the cognitive processes with respect to engineering design. Instructors for courses where the learning aid could be used served as mentors for the cognitive process of the technical concept addressed by the learning aid. These latter instructors have various levels of interest in implementing design activities in their courses and have different levels of familiarity with formal design methods. In this way, we aim to improve the design decision-making skills of undergraduates using a cognitive apprenticeship-based design activity. This activity is intended to enable design throughout the curriculum by utilizing students as the mechanism and a specific design course as the medium for this goal. That is, students are themselves the mechanism for identifying the conceptual gaps and potential design activities that can address those gaps. Additionally, the design course serves as a medium for addressing those gaps in other courses.

We describe this paradigm as a "Centralized Generative Design" approach. This contrasts with other paradigms where capstone design activities connect supporting courses (traditional model) or where integrated design activities are carried through courses (integrated model). This conceptual distinction is described in Fig. 1. In the traditional paradigm, design skill and mastery of technical areas is demonstrated by a single design activity at the end of a student's education. This model serves many schools well because it allows faculty to focus on their individual expertise areas and focus resource and time intensive design activities when students have the technical expertise to be successful. However, students may not gain significant design skills and often struggle to understand how the technical areas of engineering are related to each other. An integrated model, where design activities carry over from one course to another and over the years a student is in the program, is specifically intended to address this perceived lack of connection [37]. For example, this is a major element of the Conceive, Design, Implement and Operate (CDIO) model [19]. While moving from a traditional model towards one that implements aspects of the integrated approach we have observed several challenges. Specifically, for courses that have already been created and optimized, it is challenging to find appropriate place and time in the course schedule to implement new design activities. Further, many faculty may not have experience in creating and assessing design activities. Finally, integrating design activities that carry over from one course to another requires significant faculty coordination and is challenging to implement when many students do not follow a standard course plan.

Because of these challenges, we developed a design activity based on a centralized design

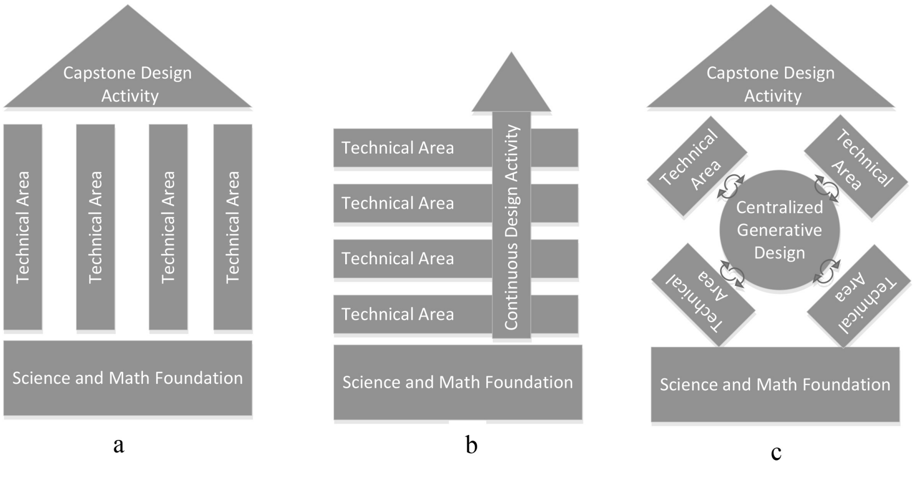

**Fig. 1.** Comparison of the traditional design education paradigm (a), more recent "integrated" design paradigms (b) and the proposed centralized design paradigm (c).

course offered in the middle of the student's education track. Using this approach, the science of designing is taught by a design instructor, the design artifacts are targeted for other technical areas and provide the desired hands-on learning through design, and there is little coordination needed across different technical courses. The drawback is that students have limited experience in the depth of the technical courses at the time when they begin the design activity.

The proposed paradigm is "Centralized" in that it feeds design activity into the other technical courses in contrast to design activities that carry in parallel across multiple courses. The paradigm is "Generative" in that it is based on the situated cognitive model of learning. Specifically, that learning is generative or a creating based activity in a social structure [38]. Therefore, learning in the technical courses is accomplished through the act of constructing knowledge and in this case, designing.

### *3.2 Implementing the centralized generative design intervention*

As discussed above, the learning theoretic framework for this intervention is situated cognition. Which stipulates that learning knowledge and skills is a social activity and should take place in the social and environmental context in which they are likely to be used in the student's non-academic life [39]. Further, the instructor's role is to scaffold the students' cognitive processes and provide authentic problems and working environment; this is called the cognitive apprenticeship. Finally, because a part of learning is social, it is important that the co-creation of knowledge happens in groups where students take on different roles. From these descriptors of situated cognition and cognitive apprenticeships, the traditional, project-based approach to teaching of design easily fits this model of learning. However, awareness of the underlying theory results in stylistic changes for the instructor. Specifically, the instructors as cognitive mentors focus on providing students with the appropriate solution finding and decision-making skills within a context similar to the real-world situation a student experiences.

The cognitive apprenticeship establishes five cognitive strategies for instructors [26]. The first strategy is modeling, where the instructor models the cognitive process. In the design context, this can look like teaching about engineering requirements by describing the thought process the instructor has while creating requirements for an actual product. The second strategy is coaching, where the instructor provides guidance while students attempt to replicate the modelled cognitive process. Using the same example, students should generate requirements for the same product in a similar process as demonstrated by the instructor. The third strategy is reflection, where students reflect on their own thinking. The fourth strategy normally follows in articulating those reflections either through writing or verbally. Students should be aware of the similarities and difference between how the instructor modelled the cognitive process. Finally, the fifth strategy of exploration requires the students to apply the cognitive process to a new problem or slightly different context. In the example, students would develop requirements for their own product.

The created intervention utilizes students to identify where in their curriculum they struggled to conceptually grasp a topic and challenges them to create a learning-aid for that course. This activity occurs in their junior year in order to enable them to have sufficient experience in the curriculum and not conflict with the students' time requirements for existing capstone design activities. The course has a typical enrollment of 80–90 junior and senior undergraduate students taught by one design instructor. Students are organized into 4 and 5-person teams for a total of 21 teams. The student groups were given the task of finding a difficult engineering concept and to create a device that would illustrate that concept. The instructor for the courses where that learning aid device could be used became both the mentor for that technical concept and the client for the final device. In total, 10 faculty served as instructor-clients. The devices the instructor-clients found useful and seemed possible to create were allowed to be manufactured. This naturally resulted in a competition between groups as some groups chose to demonstrate the same engineering concept. This is a typical outcome in real world design work. The instructor-clients met with student groups and would specifically guide their thinking processes to improve and address the fundamental concept that their device was to illustrate. In this way, they became one of the mentors under the cognitive apprenticeship learning model.

The professor of the engineering design course scaffolded students with a series of weekly deliverables. These regular assignments used traditional engineering design process and tools while following the cognitive apprenticeship model – helping to guide students through making appropriate design decisions. Specifically, student groups were required to create and submit:

1. A ranked and ordered customer requirements and preferences list.
2. A description of how they chose an ideation method followed by three detailed concepts.
3. A description of the systematic method used to

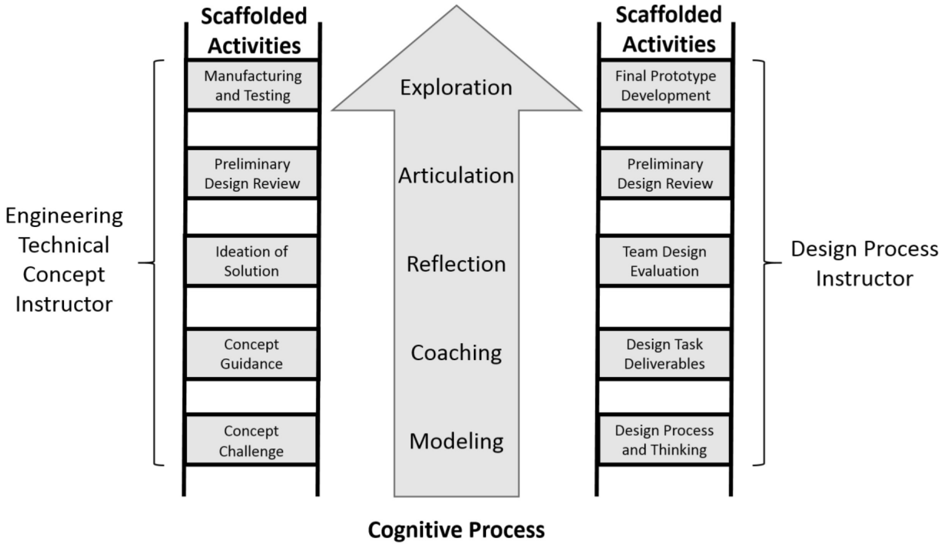

**Fig. 2.** Model of the cognitive apprenticeship implemented in this effort.

rank concepts using the customer requirements and preferences lists resulting in a functional model of a single concept.

4. Description of how they used analysis techniques to identify appropriate rough sizing of components.
5. A persuasive sales script for the prospective client.
6. A physical prototype that describes the function of the device.

In the situated cognition paradigm, there may be multiple mentors and coaches in a learner's experience [26]. In this work, one mentor is the instructor of the design process while a second mentor supports the technical concept that the student's learning aid is to address. Figure 2 describes how each cognitive apprenticeship was implemented with respect to the specific engineering technical concept and the design decision-making learning process. The five strategies of the instructor in the cognitive apprenticeship [26] are shown building on one another from Modeling to Exploration. Under these strategies, the instructors scaffold the learners with respect to their topic areas. Specifically, the technical concept instructor/client supports the team of learners through:

- Concept Challenge (Modeling): Initial meeting to provide student teams with fundamental concept where the instructor describes the appropriate way to think about the concept the learning aid is to illustrate.
- Concept Guidance (Coaching): In the initial meeting and first follow-up meeting instructor provides guidance to the students in their proposed concept learning aid.
- Ideation of Solution (Reflection): Students must generate multiple approaches to demonstrating the technical concept, reflecting on their grasp of the concept.
- Preliminary Design Review (Articulation): Students present their selected design and justify how it illustrates the technical concept.
- Manufacturing and Testing (Exploration): Students must build and implement the prototype learning aid and adjust their understanding of the concept with the reality of their device.

Additionally, the instructor responsible for guiding the students through the decision-making aspects of the engineering design process also scaffolds the students through the following specific strategies:

- Design Process and Thinking (Modeling): Overview of the structured and systematic design process with examples of previously generated products.
- Design Task Deliverables (Coaching): Students are guided through the systematic design process with specific deliverables and are required to iterate and update as design decisions are made.
- Team Design Evaluation (Reflection): Students must describe their design decision-making process they experienced during the coaching strategy.
- Preliminary Design Review (Articulation): Students must provide the justification that their product satisfies the needs of the client throughout the design process.
- Final Prototype Development (Exploration): Students make decisions on the design and man-

ufacturing methods utilizing the tools and methods modeled earlier.

## 4. Experimental results and discussion

To evaluate if the proposed centralized generative design is an effective intervention we proposed to evaluate the following two hypotheses.

1. Students gain design decision-making skills through cognitive apprenticeships as implemented in this centralized approach.
2. Student designed educational artifacts can be used to support faculty with limited design expertise or flexibility in course schedule.

To address the first hypothesis, we utilized the pre and post survey data on student's self-reported skill growth to determine if there is a statistically significant positive change. We developed a pair of Likert-scale questionnaires based on the design-skill categories developed by Gentili et al. [25]. Students completed this survey individually at the beginning and the end of the 16 week course. The second hypothesis is evaluated by exploring how the clients perceive the effectiveness of the design activity and the learning prototype to address learning in their technical courses and if the student's qualitative evaluation of their knowledge discovery through this activity. In order to investigate the second hypothesis, in the later questionnaire students were asked to assess their grasp of the fundamental concept their learning-aid addressed. The instructor-clients also completed a questionnaire that included an assessment of the group's grasp of the concept at the end of the activity. The final deliverable for this project was a report with a section for the students to answer the prompt of what they learned through the design activity. This prompt provided qualitative descriptions that address the second hypothesis. Finally, we included questions to the instructor-client on the quality of the product, their likelihood to use it in their course, and an assessment of their time contribution to the mentoring activities. The following sections detail the analysis of these two hypotheses.

### *4.1 Student design decision-making skills*

All students participating in the course were given a design decision-making skill assessment survey at the beginning and 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 Gentili et al. [25]. Students were asked to rank themselves from novice to expert (with 5 discrete levels overall). At the end of the course students were again asked to rate their skills in those exact 30 categories.

Because the intent of the survey tools was to measure any potential change in skill, the appropriate test for measuring the significance of that change is the Wilcoxon Ranked Sign Test [40, 41]. The Wilcoxon test is a non-parametric test of the significance of the difference between paired data for a single population with ordinal data. This statistical test is appropriate because the survey on individual skill levels are ordinal numbers and the surveys data is paired over the same population by asking the students to rank their skill level at the beginning and end of the course. The benefit of the Wilcoxon ranked sign test is that it evaluates the magnitude of the change in ordinal numbers and not just a positive or negative change (like a sign test). However, this test contains an implicit assumption that the distance between ordinal numbers, in this case levels of skill, is equal. Further, the Wilcoxon test evaluates the significance of the change over a population. Therefore, for students who did not report a change in a particular skill level, their results are ignored when computing if there is a significant change across all the students for that question. A 1-tailed Z-test was used to test the null hypothesis that the change in skill level is greater than zero, indicating growth in skill, with a 95% confidence level.

Table 1 summarizes the findings of completing a Wilcoxon Ranked Sign test on each of the 30 questions of the student's skill levels before and after the design activity. Only questions 1, 8, and 21 did not have sufficient evidence to determine that the change in skill was significant. Respectively, these skill questions are:

- Participating effectively in groups or teams.
- Using library resources effectively in accessing relevant information.
- Managing time and other resources as required to complete the project.

The response to question 8 regarding library search is expected, in that this activity was not specifically included in the course. This indicates that students likely entered meaningful answers into the surveys and did not report positive changes for all questions. Finding no significant change in questions 1 and 21 indicate that insufficient time was dedicated to these skills or that the presented activity did not contribute to that skill growth.

### *4.2 Student and instructor-client perception of learning-aid outcomes*

At the completion of the eight-week design portion, students were directed to meet with their instructor-clients to present their prototype for evaluation.

**Table 1.** Skill Questions and Relative Improvement Reported

| Rank | Question # | Positive Change | No Change | Negative Change | Significant at 0.05? | p-value | Data Point Removed |
|---|---|---|---|---|---|---|---|
| 30 | 1 | 29.63% | 55.56% | 14.81% | Not Significant | 0.0951 | 35 |
| 15 | 2 | 52.73% | 40.00% | 7.27% | Significant | p < 0.001 | |
| 24 | 3 | 42.59% | 44.44% | 12.96% | Significant | 0.0011 | 9 |
| 25 | 4 | 41.82% | 41.82% | 16.36% | Significant | 0.0057 | |
| 22 | 5 | 43.64% | 40.00% | 16.36% | Significant | 0.0183 | |
| 18 | 6 | 50.91% | 43.64% | 5.45% | Significant | p < 0.001 | |
| 9 | 7 | 58.18% | 30.91% | 10.91% | Significant | p < 0.001 | |
| 26 | 8 | 38.89% | 35.19% | 25.93% | Not Significant | 0.1515 | 50 |
| 7 | 9 | 61.82% | 30.91% | 7.27% | Significant | p < 0.001 | |
| 13 | 10 | 54.55% | 30.91% | 14.55% | Significant | p < 0.001 | |
| 4 | 11 | 64.81% | 25.93% | 9.26% | Significant | p < 0.001 | 50 |
| 6 | 12 | 62.96% | 27.78% | 9.26% | Significant | p < 0.001 | 33 |
| 9 | 13 | 58.18% | 27.27% | 14.55% | Significant | p < 0.001 | |
| 5 | 14 | 63.64% | 25.45% | 10.91% | Significant | p < 0.001 | |
| 15 | 15 | 52.73% | 38.18% | 9.09% | Significant | p < 0.001 | |
| 27 | 16 | 34.55% | 47.27% | 18.18% | Significant | 0.0222 | |
| 1 | 17 | 72.22% | 24.07% | 3.70% | Significant | p < 0.001 | 50 |
| 9 | 18 | 58.18% | 34.55% | 7.27% | Significant | p < 0.001 | |
| 8 | 19 | 60.00% | 27.27% | 12.73% | Significant | p < 0.001 | |
| 2 | 20 | 70.91% | 20.00% | 9.09% | Significant | p < 0.001 | |
| 27 | 21 | 34.55% | 45.45% | 20.00% | Not Significant | 0.2358 | |
| 22 | 22 | 43.64% | 47.27% | 9.09% | Significant | p < 0.001 | |
| 20 | 23 | 47.27% | 36.36% | 16.36% | Significant | 0.0016 | |
| 20 | 24 | 47.27% | 41.82% | 10.91% | Significant | 0.0016 | |
| 27 | 25 | 34.55% | 52.73% | 12.73% | Significant | 0.0089 | |
| 9 | 26 | 58.18% | 32.73% | 9.09% | Significant | p < 0.001 | |
| 14 | 27 | 53.70% | 33.33% | 12.96% | Significant | p < 0.001 | 49 |
| 19 | 28 | 50.91% | 34.55% | 14.55% | Significant | p < 0.001 | |
| 3 | 29 | 67.27% | 23.64% | 9.09% | Significant | p < 0.001 | |
| 15 | 30 | 52.73% | 30.91% | 16.36% | Significant | p < 0.001 | |

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. Sixty-five students completed this survey, 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 course students were asked if designing the learning aid deepened their understanding of the concept. Results from this question were positive and can be seen in Table 4.

The final deliverable for this design activity was a report that included a prompt for the students to define their design rationale and learning from this activity [42]. The qualitative nature of this data is difficult to reason with since a small number of samples were collected (one for each group). Discussion of these qualitative results is presented in the Discussion section.

## 5. Discussion

There are several interesting observations that we can make from the collected data with respect to the hypotheses of this work and the data collection approach in general.

### *5.1 Students improved in their decision-making skills*

Table 1 indicates that all other questions had significant skill growth at the 95% confidence level except for questions 1, 8, and 21 as discussed above. The Wilcoxon test ignores students who report no change in skill. Thus, the results can be understood as: for those who reported a change in skill level, overall, that change was positive and statistically significant. However, this does not indicate anything about the number of students who reported a change. In Table 1 the percentage of students showing positive change, no change, and

**Table 2.** Skill level Questions Evaluated by Students before and after the Design Activity Ranked on 5-Point Scale from Novice to Expert

| Question # | Skill Description |
|---|---|
| 1 | Participating effectively in groups or teams. |
| 2 | Understanding my own and other member's styles of thinking and how they affect teamwork. |
| 3 | Understanding the different roles included in effective teamwork and responsibilities of each role. |
| 4 | Using effective group communication skills: listening, speaking, visual communication. |
| 5 | Cooperating to support effective teamwork. |
| 6 | Gathering information, use various sources and techniques, and analyze their validity and appropriateness. |
| 7 | Using important visual and oral techniques (questioning, observing) for information gathering. |
| 8 | Using library resources effectively in accessing relevant information. |
| 9 | Defining problems, which includes specific goal statement, criteria and constraints. |
| 10 | Understanding what is open-ended and what is defined in problems. |
| 11 | Developing specific goal statements after gathering information about a problem (need). |
| 12 | Recognizing the importance of problem definition for development of an appropriate design. |
| 13 | Developing problem definitions with specific criteria and constraints. |
| 14 | Utilizing effective techniques for idea generation. |
| 15 | Identifying and utilizing environments that support idea generation. |
| 16 | Brainstorm effectively in teams. |
| 17 | Using techniques that synthesize ideas to increase overall idea generation. |
| 18 | Utilizing critical evaluation and decision making skills and techniques, including testing. |
| 19 | Following an iterative approach that employs evaluation repeatedly in their design process. |
| 20 | Implementing a design to a state of usefulness to prospective clients. |
| 21 | Managing time and other resources as required to complete their project. |
| 22 | Following instructions provided by others in implementation. |
| 23 | Communicating with team members at all stages of development and implementation of design solutions. |
| 24 | Practicing effective listening skills for receiving information accurately. |
| 25 | Exhibiting appropriate nonverbal mannerisms (e.g., eye contact) in interpersonal communication. |
| 26 | Giving and receiving constructive criticism and suggestions. |
| 27 | Recording group activities and outcomes, ideas, date, etc. in personal design journals. |
| 28 | Producing technical papers and memos in acceptable style and format. |
| 29 | Presenting design information in group oral presentations. |
| 30 | Communicating geometric relationships using drawings and sketches. |

negative change in skill level is shown. From these we established a Rank column to indicate which skills showed the largest percentage of positive improvement for the most students. Low ranking rows show statistical significant growth but only over a minority of students, with a large minority reporting no change. This approach can distinguish that 19 of the skills showed improvement for a majority of the students. Finally, the last column in Table 1 indicates that a participant in the study failed to provide an answer to either the first or second survey and therefor, a change could not be calculated for that participant. Table 2 lists the specific skill description for each of the 30 questions studied in this work.

An interesting point is why some students reported a negative change in skill after the design activity. There are two possibilities; (1) the presented design activity decreased the skill level of students from their perspective, or (2) the student's perspective of their skill level was re-adjusted based on being forced to apply the skills and observing others' skill level. Researchers have found that people are generally overconfident about their cognitive abilities. That is, people believe their responses to test questions are more accurate than the responses actually are [43–46]. Furthermore, students are overconfident in their learning after they have heard a lecture compared to when they have to solve a problem because the instructor's

**Table 3.** High-Level Improvement Reported by Category

| High Level Skill Assessment Questions: | | Strongly Agree | Agree | Neither | Disagree | Strongly Disagree | No Answer |
|---|---|---|---|---|---|---|---|
| By taking this course, I improved my skills in: | | | | | | | |
| 1 | Working successfully in a team environment. | 24 | 26 | 4 | 0 | 1 | 0 |
| 2 | Effectively gathering information to solve a design problem. | 20 | 26 | 6 | 1 | 2 | 0 |
| 3 | Defining open-ended problems. | 17 | 32 | 3 | 3 | 0 | 0 |
| 4 | Generating/brainstorming alternatives. | 15 | 33 | 4 | 1 | 2 | 0 |
| 5 | Evaluating and making decisions between alternatives. | 13 | 36 | 2 | 2 | 2 | 0 |
| 6 | Physically implementing a design concept. | 17 | 28 | 5 | 3 | 1 | 1 |
| 7 | Communicating project work to others. | 16 | 33 | 3 | 2 | 0 | 1 |

Table 4. Survey Responses for the Student's Perception of the Effectiveness of Creating the Learning Aid

**By creating the learning aid I have a deeper understanding of the concept the device was attempting to demonstrate.**

| Possible Answers | Number of Responses | Percentage of Responses |
|---|---|---|
| Strongly Agree | 32 | 46.4% |
| Agree | 30 | 43.5% |
| Neither Agree or Disagree | 3 | 4.3% |
| Disagree | 2 | 2.9% |
| Strongly Disagree | 2 | 2.9% |
| Cannot Answer | 0 | 0% |

Table 5. 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 6. 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 |

knowledge and understanding is mistaken to be one's own [47, 48]. The problems given to students probably pushed them to realize what they did not understand, whereas in the lecture condition, they thought they knew more than they did. Previous research has suggested that undergraduate students consider learning to occur when an "expert" transmits factual knowledge and not when it is constructed via experiential learning [49]. Additionally, previous findings have indicated that students perceive traditional lecture to be more effective compared to active learning methods even though students' learning outcomes were found to be higher in active learning courses [50, 51]. Research on the use of student-centered teaching within engineering has also found that students feel that less content is covered when inductive teaching is used when compared to deductive lecture-based approaches [52]. Research from psychology has suggested that students' judgments of learning may not be accurate predictors of their actual learning outcomes [53, 54]. Glenberg, Wilkinson, and Epstein found that students have an "illusion of knowing" and tend to be overconfident in their understanding of the material [54]. Given that the majority of the research on active learning activities similar to those reported in this paper focus on student perceptions, it is important to examine whether perceptions are an accurate predictor for learning in this context.

As indicated earlier, it is most likely that the question regarding library search (question 8) was not significant because that activity was not specifically included in the course. Finding no significant change in questions 1 and 21 may indicate that insufficient time was dedicated to initial socialization between team members [55] or to defining clear team roles [56], both of which are factors that have shown to increase newcomer adjustment to the cognitive apprenticeship model. Future research should examine the influence of initial socialization between team members and the defining of clear team roles on team based skills in engineering design courses.

From these observations, we believe it is likely that students have a more realistic view of the skills and, in general, those skills improved as a result of the design activity. However, it is important to note that from the data used in this study is not possible to determine if students developed a more realistic view of their own skills.

### *5.2 The learning-aids students made were useful*

In summarizing the responses to the qualitative evaluation of the project in their project report, we found that for many groups, the open-ended task of creating a novel product seemed overwhelming and the structured coaching strategy of the apprenticeship was very important. For other students who felt more confident in the ability to create an artifact, the structured thinking process addressed common pitfalls of engineering design such as fixation. For the group that designed the spring-mass system shown in Fig. 3, the group quickly fixated on an automotive inspired approach that used a shaft and cams to separately move the two spring-masses. However, through coaching and being required to quantitatively compare alternative solutions, the group discovered that a circular rotating cam shown on the right of Fig. 3 utilized less parts and was simpler

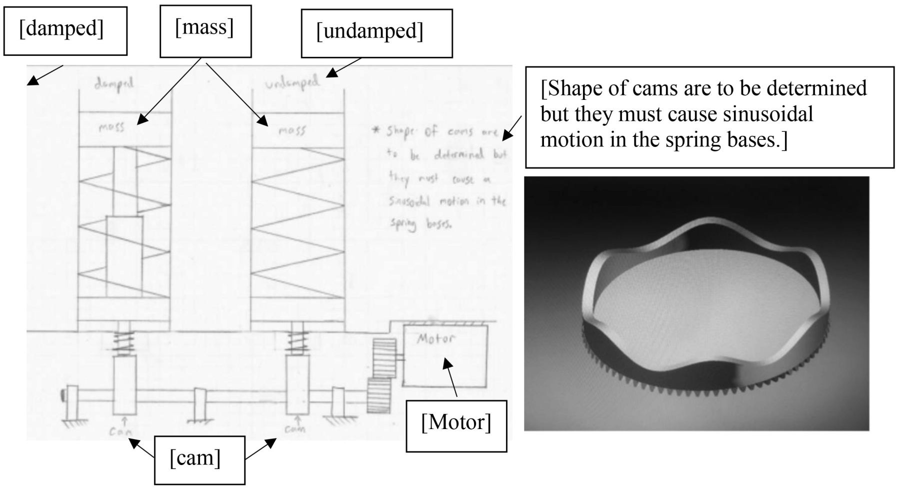

**Fig. 3.** A prototype device to illustrate damped and undamped vibration using a unique sinusoidal cam to drive the spring-mass system.

and cheaper to manufacturer than the initial separate cam system. One group reported that, after building their first conceptual prototype for a device demonstrating the mechanical advantage of multiple pulleys, they discovered their original design mounted the pulleys in such a way as to eliminate the mechanical advantage. This demonstrated to the group that they lacked the intuition-level knowledge of that concept.

From these comments, we believe that, using this centralized generative design paradigm, students acquired an applied understanding of how engineered systems are designed as well as utilized their knowledge of other engineering concepts to create the learning aids. Additionally, utilizing the cognitive apprenticeship model for guiding the student groups through the systematic design decision-making process was equally useful for supporting both students with low confidence or skill in design and those more experienced in creative projects.

Many instructors rely on physical and virtual learning aids to convey content to students. Based on this work, we see evidence that making students the designers of their own learning aids is more effective than being passive recipients of pre-made learning aids. Students self-examining their own knowledge reported 89.9% agreement that the activity of making a learning aid deepened the understanding of the concept. The activity of making something which teaches a concept requires students to confront misconceptions and provides them confidence in their ability to communicate fundamental concepts. This confidence can be seen in 78.4% reporting their clients were satisfied with the conceptual prototype the group generated. Based on these results we conclude that engaging students in the construction of learning aids likely enables a deeper understanding of concepts when compared to passive observation of learning aids in their course work.

## 6. Conclusions

In this work, we are interested in overcoming the challenges of implementing design activities throughout the engineering curriculum. Often this challenge is interpreted as identifying how to implement a number of design experiences in various courses not specifically about design. Instead, we pursued a centralized generative design paradigm where design-decision making is taught in a single design specific course while the designed artifacts are intended to address the learning needs in other technical courses. The learning theory underlying this approach utilizes a cognitive apprenticeship.

The evaluation of the efficacy of the centralized generative design paradigm explored in this paper is based on measurably improving design skills and evaluating how the artifacts implement the goal of design throughout the curriculum. We found that there was statistically significant improvement in several design skills. The design of learning aids for instructors acting as clients served as a feasible implementation of this learning paradigm. However, the instructors filled both the role of mentor and client, which might include conflicting priorities. Future work will focus on separating these role holders. Based on the successful generation of prototypes and their reported satisfaction level, we believe this activity was an effective tool for allowing the students to experience design work in an authentic way. Further, students self-reported discovery of misconceptions through the learning-aid design process. Students observed directly what happened in engineering design, modeled the practice of their teacher, reflected on the ideas they learn through an authentic, real-life design process, and addressed any related misconceptions of other technical areas. The instructors encouraged the development of design knowledge in the student groups by making tacit knowledge explicit, modeling effective strategies for completing tasks, providing scaffolded support when students were practicing new tasks, and offering specific feedback for improvement. This apprenticeship was vitally important for the transferability of engineering design knowledge into actual practice.

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