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Design thinking concepts in Undergraduate Engineering Capstone Projects

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WIP: Design thinking concepts in Undergraduate Engineering Capstone Projects

Introduction: Part of the successful assessment of an engineering program includes the description of a "major design experience that prepares students for engineering practice" (ABET EAC 2019-2020 Criterion 5 A.7). In addition, the revised student outcomes for the 2019-2020 cycle and beyond, requires programs to evaluate students' "ability to apply engineering design to produce solutions that meet specified needs…" (ABET EAC 2019-2020 SO 2). This major design experience, typically a senior capstone project, should include the culmination of the foundational materials students learn during their course of study. ABET has also defined "engineering design" which includes many concepts of Design Thinking (DT). DT is a multistep process that begins with the formalization of the problem statement and moves through implementation of possible solutions with the needs of the end-user in mind. There are several 'flavors' of design thinking available and we have been following the 5-step design thinking process described by Plattner 2010 where the process moves through 'empathize, define, ideate, prototype, and test'[1] and the biodesign process described by Yock, et al.[2]

Our college has been introducing DT concepts in our first year Introduction to Engineering course (ENGR 1101) and our senior design (SD) series (ENGR 4169 and 4269) since 2014. These courses are required for every engineering student in our college. As a bioengineering department, we have also included design thinking within our required, introductory bioengineering course since 2014, as well as, two newly developed elective Biodesign courses started in 2018. Our goal is to determine if our intervention has made an impact on the design thinking mindset of engineering students as reflected in their culminating design experience. The final design document from the last senior design course was chosen for evaluation as a "living document" of the student team's process through their capstone projects and should contain information about the design thinking process used by the students as they completed their projects. This project evaluated the efficacy of incorporating design thinking concepts within the mindset of our undergraduate engineering students by evaluating SD team final design documents from their senior capstone experiences. This is the first comprehensive exploration of design thinking within our college and provides a baseline of our students' application of this process to an open-ended engineering design project.

Methods: Final design document from 56 Spring semester 2018 graduating engineering student teams were evaluated using an in-house rubric for DT concepts.[4] The SD design documents covered a range of topics related to the four engineering disciplines taught in the College of Engineering. The student teams, which are typically made of 3-4 students, could have members from any of the engineering disciplines. The SD project topics tended to have a focus in one of the engineering disciplines, for example Bioengineering, but could have elements of other disciplines. The projects by discipline were 11 Bioengineering (BE), 15 Civil Engineering (CE), 8 Electrical/Computer Engineering (ECE), and 22 Mechanical Engineering (ME). The students are given a general template for writing their reports that includes executive summary, problem description, design criteria, solution description, testing and results, budget, and future work.

The SD documents were evaluated by 5 graduate students that had no interactions with these SD teams nor had participated in any role in the courses or programs related to design thinking offered by the college. Each rubric was based on a 4-point Likert scale and ranked from 4 (master) to 1 (novice) based on multiple DT concept categories. These categories were defined as problem description, needs statement, design criteria, multiple solutions, prototype creation, component testing, final prototype testing, and context. The SD design documents were reviewed to determine if these items were mentioned and described based on the defined rubric levels. These rubric criteria were linked to the 5-step DT process, where 'empathize' – problem description; 'define' – needs statement and design criteria; 'ideate' – multiple solutions; 'prototype' – prototype solutions, and 'test' - component testing, final prototype testing, and context. Here 'context' is an important step to determine if students can 'close the loop' relate how their final solutions address the initial problem in addition to relating their projects in the greater societal arena.

Intraclass correlation coefficients (ICC) are an established method of evaluating observer reliability.[4] ICCs were calculated in three ways; comparing "All Scores" for each grader (448 subjects - 8 DT concepts from each of 56 teams), comparing "Team Average" scores for each grader (56 teams), and comparing "DT Concept Average" scores for each grader (8 DT concepts). The "irr" package function "icc" in the R programming language using the two-way effect randomization model automated the ICC calculation.[5] Correlations were considered "fair" for ICCs ≥ 0.4, "good" for ICCs ≥ 0.6, and "excellent" for ICCs ≥ 0.75 per established methods.[6]

To assess if grading biases between graders affected the results, all scores were normalized and re-evaluated according to the above ICC criteria. Scores were normalized by dividing the global average of all scores by the average of each grader to produce a normalization ratio for each grader. Each grader's scores were then multiplied by their respective ratios. The non-normalized and normalized scores are referred to as "raw" and "adjusted" for the remainder of this article.

To assess if differences were observed between scores provided for BE versus other departments, multiple two-tailed student t-tests were performed between the values for each DT category. The Bonferroni method was used to correct for multiple comparison errors. Results were considered significant for p-values less than 0.001.

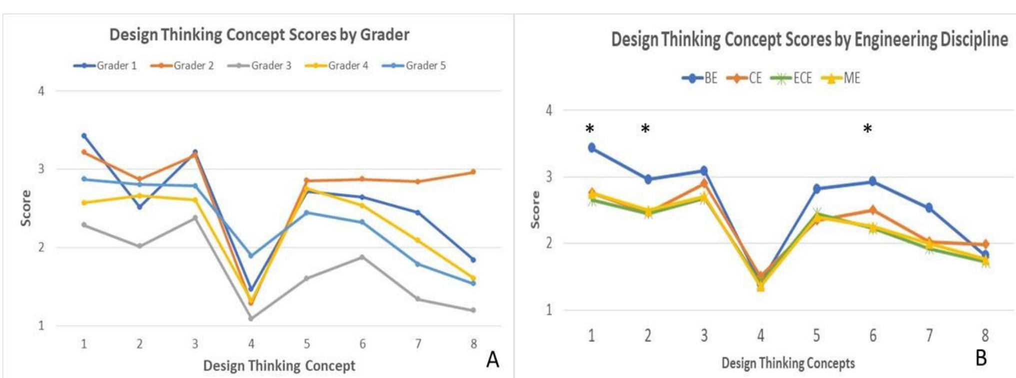
Results: Graders reported that the rubric provided specific and easy-to-follow guidelines for scoring teams against each DT concept. Average raw scores of each of the five graders for each DT concept are shown in Figure 1A; however, error bars are not shown due to high variability between SD teams. Specifically, the average team seems to perform worse in the DT concepts "Multiple Solutions", "Final Prototype Testing", and "Context". A breakdown of these concepts by department shows that BE focused teams scored higher than other disciplines in "Problem Description", "Needs Statement", and "Component Testing" as averaged across the five graders. ($p<0.001$) (Figure 1B)

The obtained ICC values between the "raw" and "adjusted" scores showed, at most, a 2% difference and all were at least 0.42 indicating a "Fair" correspondence between graders with 'raw' and 'adjusted' overall DT concept averages with ICC values > 0.75 or "Excellent" correspondence. Since correlations were observed between the graders, the rubric can be described as a consistent tool for evaluation of senior design documents for these DT criteria.

Discussion: In this manuscript, we have established a baseline indication of how training of DT concepts has been internalized by our senior design students through the review of their design documents for their culminating design experience as undergraduates. The student teams seem to be fairly strong at defining the problem that they are working on and defining the design criteria that they need to meet in order to show that their proposed solutions appropriately addressed the problem. In addition, the teams were able to show that they created an initial prototype device, model, or process. The teams were less able to show evidence of the evaluation of multiple solutions before they selected a final solution concept. In addition, they were less able to show any optimization of their initial prototype to create and test a ***final*** prototype, as well as, be able to place their designs into a larger context, such as global, regulatory, ethical, etc. This report cannot show that these concepts were not considered by the teams, just that they were not reported in the final design documents. Emphasis of reporting these concepts in the documents could be a relatively easy fix if this were the issue.

The data presented also represent an average scoring across SD design documents from all departments. Not all teams created a device that could be improved through iteration or had different components that could be tested and thus were considered more difficult to score, such as teams that had "virtual" prototypes, for example a civil engineering traffic flow improvement design project. However, differences were observed in the total average scores provided by each grader, the limited change in ICC value before and after normalization of the data indicates the differences are not substantial enough to affect correlation.

A review of these DT concepts by department showed that BE performed significantly better than other disciplines in 3 of the 8 concepts. This can be seen as reflective of the additional training BE students have received and the DT focus of some faculty advisors for BE focused student teams. We note that BE faculty are not the only faculty that have participated in DT training at our college. Initial training in 2014 was received by faculty from each discipline. Then DT concepts were employed in our Introduction to Engineering and senior design courses which are required for every student, in addition to, our introductory BE class after this training. There are areas for improvement as only the initial steps of the DT process (1-3) scored at 3 and above in BE, indicating that more efforts on the development and testing of prototypes is required for all SD teams. We hope to show that incorporation of DT process in BE improves the overall student work product (used as a proxy for student learning) in senior design so that these methods can be disseminated throughout our engineering college. Anecdotally, the authors have also noted that students do not naturally use DT process in subsequent classes, so early and repeated exposure to the DT concepts is important for enhanced student internalization of design thinking in open-ended projects. This will be determined as we review SD design documents from subsequent semesters to determine if natural revisions in teaching and additional elective biodesign materials have improved student outcomes.



Design Thinking Concept	Number
Problem Description	1
Needs Statement	2
Design Criteria	3
Multiple Solutions	4
Prototype Creation	5
Component Testing	6
Final Prototype Testing	7
Context	8

*Figure 1: A) Average scores of DT concepts for each of the five graders. B) Average DT concept scores separated by engineering discipline. Scoring was based on a Likert scale, where 1–low and 4–high. The eight concepts that were scored are listed on the right. * $p<0.001$ BE vs. others*