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SHORT PAPERS: AN INITIAL ANALYSIS OF UNDERGRADUATE STUDENT MENTAL MODELS OF PRODUCT DESIGN

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ABSTRACT

Design is a concept that means different things to different people. Even in the engineering design research community, there is little agreement on a consistent definition of design. This study looks into how engineering students understand product design, using a concept mapping exercise to elicit the key concepts and relationships present in their mental models. An analysis of concept maps from 130 third-year undergraduate engineering students shows how these students think about design, the common themes and relationships that are seen across the population, and variations across different groups of students. By understanding how students in the midst of ABET-accredited programs conceptualize design, conclusions can be drawn regarding the effectiveness of existing curricula in instilling a complete understanding of holistic product design. This can lead to recommendations regarding future engineering design learning objectives, teaching materials, and activities.

INTRODUCTION

Product design has been taught in undergraduate engineering programs for decades. Entire courses are devoted to this subject, giving students opportunities to practice design through project-based learning. However, this is a challenging topic on which to assess learning, as design is a multi-faceted and sometimes ambiguous concept. The objective of this study is to explore how undergraduate students think about product design and the main topics that they internally connect to product design. By engaging students in a concept mapping activity at the beginning of a product design course, key themes have emerged regarding how students think about design, what key concepts they associate with design, and the complexity and interrelationships within their mental models. This paper provides the early results of an analysis of 130 student concept maps surrounding the idea of "product design."

BACKGROUND

This work builds on a recognized gap in holistic design education by generating and analyzing concept maps of students' mental models of design.

Design Education

Though engineering as a practice has been around for millennia, the first schools introduced engineering as a discipline in the early 19th century. In the late 19th and early 20th centuries, the first professional engineering societies were established. In 1932, ABET was founded as the Accreditation Board for Engineering and Technology, and it quickly became the benchmark indicator of a school's proficiency in engineering education. ABET reviews and recognizes programs at colleges and universities that meet their standards for effectively preparing students for professional roles in engineering and technology. Universities that engage in the ABET accreditation process must achieve quality standards set by ABET and are under review for the duration of their accreditation. Similarly, ABET is ISO 9001

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certified, validating the entity's commitment to continuous improvement and quality, providing accreditation to the accreditation board. In line with these standards, ABET-accredited programs aim to provide students with the ability to design solutions for well-defined technical problems, and they often conclude with a capstone project or integrated engineering design experience [1].

In 1952, the American Society for Engineering Education (ASEE) appointed a Committee on Evaluation to recommend a path that would enable engineering education to produce thinkers equipped to lead in the industry 50 years later. This committee was established following the 1951 recommendation of the Engineers' Council for Professional Development (ECPD) Committee on Adequacy and Standards of Engineering Education per their discussions with ASEE due to concerns surrounding the surging advancements in technology. They determined that the trajectory of education in the field of engineering is subject to the obligations of the profession of engineering to society. Among the assertions of the council were the need for a stimulating intellectual atmosphere fueled by mutual interests as well as a profoundly intellectual faculty with qualifications as well as appreciation for the field and its objectives. The recommendations stress education in the fundamental sciences and using these sciences as the core of engineering science. Engineering design, systems, and analysis coursework follows, to target creative thinking in science, alongside elective coursework and social sciences to develop well-rounded future professionals [2].

Since then, studies have shown that engineering curricula have been too heavily focused on scientific principles, without sufficient emphasis on practical applications through design education [3]. This has led to documented under-performance of new engineering graduates entering the workforce, as well as the need for additional training before these new professionals can implement their knowledge in the context of real-world engineering decision-making [4]. To address the need for improved "design in context" education, newer approaches to holistic technical education have been put forward, such as CDIO (which stands for conceive, design, implement, operate) and Integrative STEM Education [5,6]. With this renewed push for improved design education, colleges and universities around the world have instituted design learning experiences through capstone [7], cornerstone, and even "Design Spine" sequences that students follow throughout their degree programs [8, 9]. This study seeks to understand how students in the midst of a Design Spine sequence conceptualize design, what factors are most prominent in their mental models of design, and how these factors change by degree program and demographics.

Concept Mapping

Concept maps are aids to reflect on an individual's or group's internal understanding, impression, and/or rationale of a given concept [10], and to highlight conceptual changes in those understandings over time [11]. They highlight the thought flow through an idea surrounding a concept [12]. In a concept map, boxed or circled concepts surround a central concept/theme as the nodes in a conceptual network. Concepts are linked by relationships, or the edges of the network, which are depicted as arrows with text that relates one concept to another [11–14]. The thought flows can be read as "concept-link-concept" to formulate coherent phrases, as displayed in Figure 1 through a simple mapping of key factors in the U.S. government.

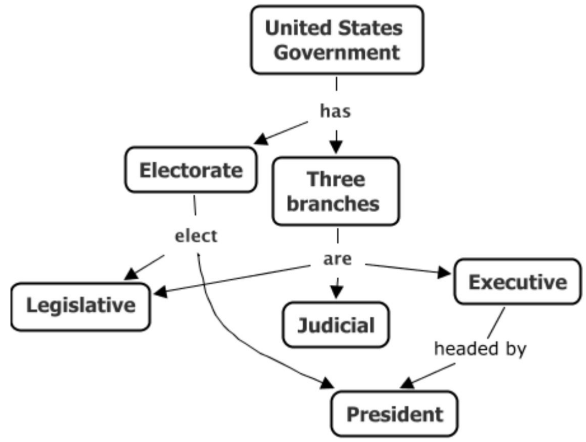

FIGURE 1. SIMPLE CONCEPT MAP DEPICTING THE U.S. GOVERNMENT STRUCTURE [15]

Concept maps have been introduced as a tool to measure the knowledge acquired by students. To measure learning resulting from instruction or exercises, it is common for students to complete a "before" and "after" concept map to be able to analyze changes or improvements in the identified concepts and their correlations [11, 14]. Concept maps can also be compared to those of experts to assess learning or mastery of material, as well as understanding of root causes. A Harvard study showed that a majority of participants could not map seasons to the fundamental reason that they occur, despite experiencing them and having been taught about them [13]; this shows how concept maps can reveal when individuals know, or fundamentally do not know, the root causes of their knowledge or preconceptions.

There are many methods for analyzing or scoring concept maps without bias. First, a concept map can be scored independently through the evaluation of its components, assessing the presence of absence of particular concepts or relationships. Another approach is to score them by variance relative to an expert or "correct" master map. Concept maps can be scored either qualitatively or quantitatively and by either their structure or the relationships identified [10, 16, 17]. In this research, concept maps are viewed objectively through network analysis techniques as well as holistically through evaluation of components.

METHODOLOGY

During the first week of a third-year undergraduate engineering design class, students in five different course sections were asked to generate concept maps around the phrase "product design." As most of the students were not familiar with concept mapping, and to ensure that all students were on the same page regarding proper concept map construction, this class session began with a brief review of the purpose of concept maps and their structures. Two small example concept maps were shown to the class, one about nuclear reactors and one meta-example of a concept map about concept maps. Then, in a group exercise led by the instructor, the class collectively generated a concept map on a whiteboard around the idea of "personal health," which often included concepts related to mental health, physical health, nutrition, exercise, sleep, and hygiene. Then, each student received a ledger-sized (11 x 17 inch) sheet of paper and a pencil, and they were given 15 minutes during class to draw a concept map using the following prompt along with Fig. 2:

Draw a concept map that embodies the concept of "product design." There is no right or wrong answer, as we just want to explore how you think about product design and the factors that are important to consider in product design. Please use the entire 15 minutes to add/revise elements and refine the structure and connections. Remember, concept maps include concepts (in boxes) and relationships (along arrows).

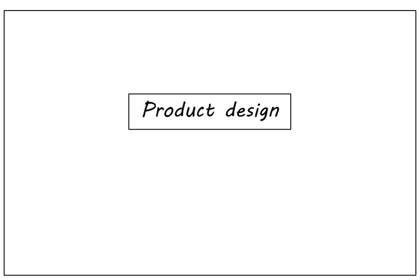

FIGURE 2. CONCEPT MAPPING EXERCISE PROMPT.

The participants included five course sections of students enrolled in *Engineering Design VI* in the Mechanical Engineering (ME), Engineering Management (EM), and Industrial & Systems Engineering (ISE) programs during the Spring 2020 term. This course is so named because it is the sixth in an eight-course *Design Spine* sequence at the institution that emphasizes design learning throughout the curriculum. The study included 130 students: four ME sections with 109 total students, and one combined EM/ISE section that included 18 EM students and three ISE students. Prior to the concept mapping activity, the participants signed voluntary informed consent forms to permit inclusion in the study. The research plan was approved by the Stevens Institute of Technology Institutional Review Board (IRB) under protocol number 2017-016 (20-R1).

RESULTS

The analyses of these concept maps investigate the connections made as well as the network structure and links. This includes network metrics such as numbers of nodes and edges, counts of different included concepts, commonalities and differences across different participant groups, and the direction of influence of each concept. The results presented in this short paper provide an overview of these counts, as well as some early analyses of the statistical differences across participant groups.

The study also takes an interest in whether terms are most distinctly used as a source or a target by the edge links. This examines each concept to see whether its edges are directed away as outflows or towards them as inflows. In this preliminary investigation of the concepts' directions, all map source and target counts are compiled into a "net flow" metric, where a positive net flow indicates more edges directed toward a concept than away from it.

Network Analysis

The collected concept maps had a mean of 15.7 concepts per map, with a range from 7 to 29 nodes. While the range was broad, the median was 15 nodes, showing no substantial skew in the distribution. Similarly, the concept maps had a mean of 22.2 edges, ranging from 8 to 47 edges. From a network analysis standpoint, the potential connections (*PC*) of a network is the number of edges a network with n nodes could have supported if every node were connected in both directions to every other node, calculated using Eqn. (1).

$$PC = n(n-1) \tag{1}$$

This capacity of the network comes into play when determining the density of the network, given by Eqn. (2), where *AC* is the number of actual connections, or edges.

$$Density = \frac{AC}{PC} \tag{2}$$

The average nodes, edges, and network density across the five class sections are detailed in Table 1.

Sections A, B, C, and D consist of ME students, and section E includes a combination of EM and ISE students. Two-sample t-tests assuming unequal variances are conducted on the average nodes, edges, and density of the concept maps in different sections, with the null hypothesis that there is no systematic difference in network metrics between sections A-D (ME) and section E (EM/ISE). The results from this statistical analysis are shown in Table 2. These results reject the null hypothesis and demonstrate a statistically significant difference in the concept maps developed by ME students versus those produced by EM and ISE

TABLE 1. AVERAGE NETWORK ATTRIBUTES BY SECTION.

	A	B	C	D	E	All
Subjects	27	26	31	25	21	130
Nodes	15.5	15.6	15.5	16.4	20.7	15.7
Edges	20.6	24.7	19.5	21.6	25.7	22.2
Density	0.112	0.123	0.105	0.094	0.069	0.102

TABLE 2. AVERAGE NETWORK ATTRIBUTES AND STATISTICAL TEST RESULTS BY DISCIPLINE.

	A-D (ME)	E (EM/ISE)	*t* stat	*p* value
Subjects	109	21		
Nodes	15.7	20.7	-3.61	$< 0.001^{***}$
Edges	21.5	25.7	-2.13	0.022^{*}
Density	0.109	0.066	5.75	$< 0.001^{***}$

Statistical significance levels: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

TABLE 3. AVERAGE NETWORK ATTRIBUTES AND STATISTICAL TEST RESULTS BY GENDER.

	Female	Male	*t* stat	*p* value
Subjects	33	97		
Nodes	17.8	16.0	1.49	0.071
Edges	22.9	21.8	0.738	0.232
Density	0.094	0.106	-1.10	0.139

students in numbers of concepts, links, and density. Similar t-tests were conducted between the individual ME sections (A-D), finding no significant differences among those sections.

The next statistical analysis tests the null hypothesis that there is no significant difference between the average nodes, edges, and density of concept maps produced by male and female students across all class sections. The results of these t-tests by gender are shown in Table 3. These results support the null hypothesis that there is no significant difference based on gender alone.

However, there is a significantly higher proportion of female students (9) to male students (12) among the EM/ISE students than the ME students (24:85). To further examine this, bi-attribute two-sample t-tests assuming unequal variances test for systematic differences in network attributes based on combined discipline and gender. These tests compare female EM/ISE students' maps against female ME students' and male EM/ISE against male ME, holding gender as a constant. They also compare male and female maps while holding discipline as a constant. The statistical breakdowns for these groups are shown in Table 4, and the bi-attribute analysis results are provided in Table 5.

TABLE 4. BI-ATTRIBUTE AVERAGE NETWORK ATTRIBUTES BY DISCIPLINE AND GENDER (F = FEMALE, M = MALE).

	ME, M	EM/ISE, M	ME, F	EM/ISE, F
Subjects	85	12	24	9
Nodes	15.5	19.4	15.8	22.0
Edges	21.6	23.1	20.8	26.6
Density	0.110	0.071	0.107	0.062

TABLE 5. BI-ATTRIBUTE COMPARISON RESULTS BY DISCIPLINE AND GENDER (F = FEMALE, M = MALE).

Condition Summary	Metric	*t* stat	*p* value
ME v. EM/ISE (F only)	Nodes	-2.59	0.013^{*}
ME v. EM/ISE (F only)	Edges	-2.10	0.031^{*}
ME v. EM/ISE (F only)	Density	3.41	$< 0.001^{***}$
ME v. EM/ISE (M only)	Nodes	-2.13	0.027^{*}
ME v. EM/ISE (M only)	Edges	-0.576	0.287
ME v. EM/ISE (M only)	Density	3.79	$< 0.001^{***}$
M v. F (EM/ISE only)	Nodes	-1.43	0.086
M v. F (EM/ISE only)	Edges	-1.26	0.112
M v. F (EM/ISE only)	Density	-1.35	0.098
M v. F (ME only)	Nodes	-0.319	0.376
M v. F (ME only)	Edges	0.663	0.255
M v. F (ME only)	Density	-0.351	0.364

Statistical significance levels: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

The *t*-test results in Table 5 show significant differences in network attributes, namely nodes and densities, between disciplines when controlling for gender, and no significant differences between genders when controlling for discipline. The results mirror the single-attribute conclusions, rejecting the null hypothesis on the grounds of discipline while failing to reject the null hypothesis regarding gender. The bi-attribute examination shows that the results were not significantly impacted by gender imbalance across disciplines and affirms that strictly the disciplinary difference is supporting this pattern.

Thus, the network analysis t-tests show statistically significant differences between the majors, with ME students producing concept maps with fewer nodes and edges, yet higher densities, than the EM/ISE students. On the other hand, there were no statistically significant differences based on gender.

Concept Analysis

The 130 concept maps included 668 unique nodes, of which 64 percent were mentioned by only one student, and only 6 percent were mentioned by ten or more individuals. Every student included *product design* as the central node of their concept map, as they were instructed to do. After *product design*, the top ten nodes included:

1. prototype (mentioned by 66 individuals),
2. problem (57),
3. testing (46),
4. materials (41),
5. research (41),
6. product (41),
7. idea (37),
8. cost (33),
9. user (33), and
10. marketing (31).

Similarly, there were 2,251 unique edges, or links, pairing nodes across all of the concept maps, but only 39 percent were mentioned more than once, and only ten were repeated by ten or more subjects. These top ten edges are:

1. product design-problem (23 individuals),
2. prototype-testing (19),
3. product design-prototype (15),
4. product design-product (15),
5. product design-idea (12),
6. idea-prototype (12),
7. problem-solution (12),
8. product design-planning (11),
9. product design-testing (11), and
10. product design-research (10).

Only three of these top ten exclude *product design*.

To examine the directions of the edges connected to each node, net flows were calculated. The most frequent node, *product design*, was used as a source twice as often as it was used as a target (431 versus 216), which yields a net flow of -215. The other terms with a net flow of magnitude greater than ten are shown in Table 6. Note that one concept map may yield multiple contributions to the net flow numbers associated with a single concept, as concepts are commonly mapped with more than one edge.

TABLE 6. DIRECTED NETWORK ATTRIBUTES: NET FLOW ANALYSIS.

Term	Source	Target	Net Flow
Research	86	47	-39
Problem	65	87	22
Solution	26	47	21
Profit	9	28	19
Idea	72	54	-18
Money	32	50	18
Prototype	99	114	15
Constraints	20	7	-13
Brainstorming	23	12	-11

While *prototype* made the top ten list with a net inflow of 15, the difference between inflows and outflows may be less significant when we consider the frequency of its occurrence. Another interesting observation in the net flow analysis data is that *competitors*, *properties*, *needs*, and *economic viability* were all mentioned as targets more than five times, but these were never used as sources.

DISCUSSION

While this study is a work in progress, some interesting findings have already emerged from the included concepts and their most frequent connections, as well as some disciplinary differences. By discipline, ME students have exhibited higher average density but lower average concepts per map than the EM and ISE students. This suggests that EM and ISE students have more breadth in their conceptual models of product design, whereas ME students conceptually focus on the depth of connectivity with fewer concepts. By gender, no clear trends emerge, but this could potentially be attributed to the relatively small sample of female students. The bi-attribute analysis that split participants by gender first, then by discipline emphasizes the difference between the disciplines, affirming that the higher proportion of female students in the EM/ISE class section is unlikely to be a cause of the network attribute differences seen between the disciplines. Furthermore, even within disciplines, there is no statistically significant difference in the network attributes of the concept maps between genders.

Of the most commonly occurring pairs unaffiliated with the concept *product design*, most are associated with ideation, users, prototyping, costs, and testing. These are fundamental correlations to product design that also show up in the list of top 10 concepts. It may also be surprising that fewer than half of students considered many concepts that are considered essential to product design, such as *problem*, *user*, *research*, and *idea*, considering that all engineering design processes involve these key elements. Overall, the results showed surprisingly few commonly chosen links among the study participants. Further, the high net flow values of certain terms, such as *product design*, *research*, *solution*, *profit*, *constraints*, and *brainstorming*, show some consistencies in the ways that students think about them as sources (negative) or targets (positive).

FUTURE WORK

In addition to these concept maps collected at the beginning of *Engineering Design VI*, the project plan includes the collection of a second set of concept maps at the end of the semester, after the students have engaged in a semester-long project-based course on design. Once the post-course concept maps are collected and coded, it will be interesting to see whether the post-course concept maps have similar or statistically different network characteristics, as well as which concepts and links become more or less prevalent. It will also be interesting to examine correlations between map size and quality of concepts recognized, if the instructors and researchers can develop meaningful measures of concept quality.

Building on the bi-attribute testing of network attributes, future work will also examine how the content differs across different degree programs and genders. This could reflect a combination of the learning that takes place in the degree programs as well as the conceptual focal points of the types of students that select each degree program, as well as potentially their backgrounds and demographic characteristics.

Future analysis steps include a clustering analysis on the included concepts, to group together similarly-themed concepts and relationships, along with additional statistical comparisons. Statistical tests can be used to compare network metrics between the pre-course and post-course concept maps, between maps that included specific concepts or themes versus those that did not, and between maps divided based on some numerical threshold for nodes, edges, or densities.

One recommendation for future research on engineers' conceptualizations of design is to gather additional background data on the participants prior to collecting data, and conducting the analysis in the form of a brief survey. In the present study, such background data were not collected, limiting the demographic comparisons to gender and discipline. It would be interesting to learn more about the participants to enable comparisons based on prior work or internship experience, educational path, or other individual characteristics.

To conduct a more holistic analysis, a comparative analysis against an expert or master map may give some valuable insights into the impact of experiences. Further, examining common nodes and pairs as well as net flow variance by gender and discipline would shed light on additional differences based on these two criteria. These differences may lead to inferences about the different concepts that males versus females and ME versus EM/ISE students tend to focus on or conceptualize within product design.

The results presented here represent a first step toward understanding how engineering students conceptualize and learn about design. By conducting similar exercises at different stages throughout different undergraduate engineering programs, and mapping the results to assessments of performance in design activities, we can better understand how students learn, which concepts stick, and where there are opportunities to improve holistic design education.

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