Studying Changes using Concept Maps in First-Year Students' Understanding of the Engineering Design Process

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Abstract

This Complete Evidence-Based Practice paper investigates how first year students' understanding of the engineering design process changes in a design-based Introduction to Engineering course. This fifteen-week two-credit course introduces the engineering design process and provides students with opportunities to practice applying the engineering design process. Students were engaged in a two-week conceptual team design challenge and a ten-week hands-on team design project. In two sections of this course taught in the Fall 2018 semester with approximately 38 students each, students individually created visual representations in the form of concept maps to show their understanding of the engineering design process three times during the semester, once before the course started, once after the two-week design challenge and once at the end of the semester after the ten-week design project. Qualitative research methods were used to analyze these concept maps. Two researchers identified themes as a theoretical framework and independently coded the data based on the themes, compared and discussed discrepancies until agreement was reached to ensure inter-rater reliability. Thematic analysis of the data shows that there is no difference in students' understanding at the start of this course regardless of whether they had prior knowledge and experiences about engineering design or not. Data shows that through this course, the two-week design challenge in particular, students' understanding of the design process in all aspects has greatly improved; and students' understanding was further improved after the ten-week design challenge in areas of 'customer involvement throughout the design process', 'research/information gathering', 'model/analysis', and the 'iterative characteristic' of the design process. A weakness that was found in students' understanding at the end of the course is that most of them were only able to identify one type of information, i.e., existing solutions, for the 'research/information gathering' phase of the design process.

Introduction

In the NAE "The Engineer of 2020" report, engineering is described as being "about design under constraint" [1]. ABET criteria (c) and (e) also clearly emphasize students' ability to design a system, process, or product to meet desired needs under constraints [2]. As the central activity in engineering, design must be taught and applied in the engineering curriculum in order to prepare next generation engineers who are able to create value for the society through design. The engineering design process has become one of the main topics in first year introductory courses and many incorporate design activities such as hands-on design projects to help first year students practice applying the design process and gain design abilities and skills [3]. Are these first year courses effective at helping students better understand the design process? Most of the assessments of such first year courses have focused on students' motivation, retention, self-efficacy, engineering identity, etc. [4-7]. Assessment of the design process knowledge has taken the form of surveys; close-ended questions such as multiple choice questions; open-ended questions such as reflections and essays; talk-aloud protocols; performance of final designs; design reports; etc. [8-11]. Saterbak and Volts [12] and Zhu and Mertz [13] used students' critique of a Gantt chart that lays out a flawed proposed 14-week design process, an assessment tool developed by Bailey et al. [14] to assess students design process knowledge in their introduction to engineering courses. Each of these approaches has its strengths and weaknesses [14]. For example, some approaches such as design reports or presentations are usually done at a group level rather than at an individual level. Approaches that are based on performance of final designs are not process focused and there may be potential reliability problems with raters. In addition, the design process knowledge can span multiple levels of Bloom's Taxonomy but some of the assessment approaches are only linked to the lower levels or the application level of Bloom's Taxonomy [14].

Concept maps [15] are graphical node-arc representations that depict relationships among concepts. They have been used quite extensively both as an instructional tool and an assessment tool in science and engineering classrooms. For example, Sanford Bernhardt and Roth used concept maps of "what is engineering?" that students generated at the end of the semester to understand students' learning in their first year course [16]; Barrella et al. gained understanding on students' conceptualization of engineering decision making through the analysis of student generated concept maps in their introductory engineering course [17]; and in [18], students' conceptual understanding of engineering dynamics was assessed using concept maps.

In the research effort presented in this paper, concept mapping is used to evaluate students' understanding of the engineering design process in an Introduction to Engineering course, more specifically through the thematic analysis of the concept maps about the design process that students created individually three times throughout the course. Concept mapping was chosen as the tool for this purpose because compared to other tools, it is independent of any design projects or activities; can be easily done at the individual level; and its open-endedness requires students to internalize the knowledge, identify key concepts that are relevant, and document relationships between the concepts, demonstrating knowledge of the engineering design process at multiple levels of Bloom's Taxonomy.

In the sections below, specifics about the design-based Introduction to Engineering course will be described. The research aim, method, and a complete analysis and results will also be presented and discussed.

Context

At Arizona State University, Introduction to Engineering is a two-credit 15-week team and design based course taken by mostly first year engineering students in their first semester. It is taught in sections of approximately 40 students each with a weekly 50-minute lecture and a 3-hour lab. The course focuses on the engineering design process, basic engineering tools, and both technical and nontechnical skills. During the Fall 2018 semester, two of the sections involved in this study taught by the author covered the following topics: engineering design process, opportunity identification, problem definition, design requirements and criteria, Analytical Hierarchy Process (AHP), brainstorming techniques, making informed design decisions, modeling, descriptive modeling, orthographic drawing, Autodesk Fusion 360, predictive modeling, empirical models, financial decision making, project management, Gantt chart, technical communication, as well as a few technical topics that are relevant to the design project. Throughout the course, students worked on a two-week team design challenge and a ten-week team design project.

The two-week design challenge provides students with an opportunity to apply some of the phases of the engineering design process including identifying an opportunity, defining the problem, researching, brainstorming, decision making, and prototyping of a conceptual design. The goal of the project is to revitalize the ‘A’ mountain (an important landmark which is partially located at the university’s main campus). Three main stakeholders were introduced each having specific interests in this ‘public works’ project. Three teaching staff members each acted as one of the stakeholders and students were able to interact with these stakeholders throughout the project.

In the ten-week disaster relief project, students design an aircraft for use in various natural disaster scenarios. Fictional customers involved in this project are those working at non-profit organizations who help with disaster relief efforts. They shared their experiences and difficulties through detailed customer statements and Q & A’s. The project is broken into subsystems that are addressed one at a time though iterations are needed throughout the design, as the design changes in one subsystem would likely affect other design choices that had been made prior. Custom web-based simulators were provided to students to help them with modeling and design decision making. The final deliverables of this project include a few visual/physical representations of various aspects of the design and a design report.

Research Method

This research effort aims to understand how first year students’ understanding of the design process changes before, during, and after engaging in the class activities in this course. Data collected are the visual representations of engineering design process that students created individually three times in the semester. They will be referred to as pre-data, mid-semester data, and post-data hereafter. The pre-data were collected in a survey during the first day of class before any topics were covered. In the survey students were asked whether they had been introduced to the concept of engineering design prior to this course and if so what the occasion through which they learned about it was. They were also asked to draw a diagram (including boxes with key words/phrases in them; lines/arrows connecting the boxes to show relationships; and branches if applicable) to show the process they would use to create a design solution. The mid-semester and post-data were identical and each was collected after one of the two projects, respectively. In each case, students were asked to create a concept map showing their understanding of the engineering design process, including key steps, and possible strategies and outcomes. Students were also asked to write a short paragraph description of their visual representations each of the three times.

Out of the 74 students enrolled in the two sections of the course involved in this study, 68 provided consent to participate in this study. Out of these 68 participants, 63 responses were collected for the pre-data and the numbers are 63 and 59 for the mid-semester and post-data, respectively. Prior to data analysis, any identifiable information was removed and each of the data files was named using an anonymous code assigned to the participant. Thematic analysis of data was conducted following the process described by Braun and Clarke [19]. Four main themes were identified as a framework for thematic analysis and they are described below. The first theme was identified because of the demand of social interactions of engineers with customers in the new era of customerization [1] and the recent emphasis of the entrepreneurial mindset across the nation [20-22] and details of the other themes were based on the criteria for assessing the design process knowledge described by Bailey and Szabo [14] and Saterbak and Volz [12], as well as many other studies about engineering design [23-26]. To ensure inter-rater reliability, two raters independently coded the data, labeling evidence and specific details of each theme in the data, and compared and reached consensus for any discrepancies. The frequencies with which each theme was mentioned/represented were also counted and tabulated.

The first theme is '*Customer Involvement*'. As "the end goal [of engineering design] is the creation of an artifact, product, system, or process that performs a function or functions to fulfill customer need(s)." [27], it is very important to involve the customer throughout the process from needs analysis to gaining feedback to ensure that the design solution fulfills customer need(s) and meets or exceeds customer expectations. For this theme, when coding, data was categorized into three groups: no mention of customer; some mention and involvement of customers in the process (usually at the beginning stages for needs analysis and better understanding of the problem); and extensive involvement of customer throughout the process.

The second theme is '*Needs Analysis/Problem Definition*' in the design process. Novice designers may skip this phase and start with brainstorming, which may lead to unsatisfactory solutions or solutions to the wrong problems. Quite a few studies have found that experts spend more time analyzing problems posed than novices [25, 28-33], and many others discussed the special importance of problem formulation [34-36], for example, Jain and Sobek [36] found that student designers tend to be more effective if they spend more time in problem definition activities and that client satisfaction is associated with time spent on problem definition [36]. For this theme, details that were looked for when coding include, 'identify customer needs (and wants)', 'understand the problem', 'define goals/problem statement', 'establish requirements and criteria', etc.

The third theme is ‘*Other Phases*’ in the design process and they include research (information gathering), brainstorm, model (analysis)/decision making, create, test, and improve. This follows the design process introduced in the class shown in Figure 1 which is very similar to various design process descriptions found in literature [23-26]. Specific details that were looked for in this theme include, ‘gather information’ (importance of this is discussed in [37]), ‘research existing solutions’, ‘generate multiple ideas’ (Atman et al. found that experts generate significantly more alternative solutions than novices [25]), ‘predictive modeling (analysis) such as computer simulations, mathematical models, empirical models’ (modeling is an important design activity correlated with innovation [38]), ‘descriptive modeling such as drawings, CAD models’, ‘decision making based on criteria (such as using decision matrix)’, ‘test design against criteria’.

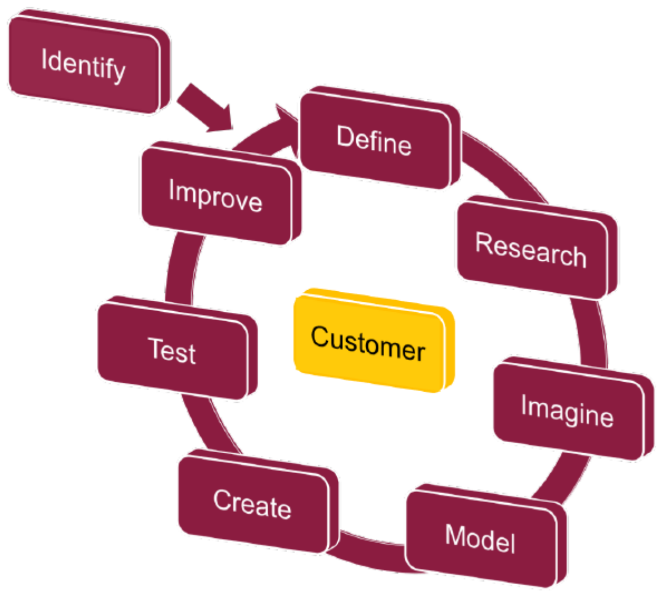

Figure 1. Engineering design process introduced in the course

The last theme is the ‘*Iterative Characteristic*’ of the design process. For this theme, data was grouped based on whether they showed a completely linear and non-iterative process, or a somewhat nonlinear and iterative process, or a completely iterative and nonlinear process. A somewhat nonlinear and iterative process may include a small loop between ‘prototype’ or ‘brainstorm’, ‘test’, and ‘refine’ whereas a completely iterative and nonlinear process may contain arrows from a phase to multiple phases, indicating that multiple previous phases especially the initial phases could be revisited. This is very important because iterations that contributed to performance were found to be often focused towards problem definition and information gathering activities [39-41].

In literature, there are two broad categories of metrics for assessment of concept maps, the ‘traditional metrics’ which focus on counting various elements in a concept map, such as number of concepts, links, hierarchies, and the ‘holistic metrics’ which include the structural complexity approaches that assess the dominant structural patterns of concepts and links and rubrics that focus on organization, comprehensiveness, and correctness of the maps [42-51]. A common element in both categories is the complexity of the concept maps, an important indicator of the quality of the concept maps and thus the level of understanding. Therefore, in this research study, besides the four themes, the concept maps were also categorized based on their richness and complexity:

- Category 1: no specific details provided in the concept map
- Category 2: more details are provided but the concept map is mostly linear
- Category 3: more details are provided and the concept map is somewhat complex but relationships between key terms are not articulated
- Category 4: concept map is complex, inter-connected, and connections between key terms are annotated

Findings and Discussions

A. Customer Involvement

For the pre-data, out of the 63 responses, 36 indicated that they had not been introduced to the concept of engineering design before this course. This group will be referred to as 'the without prior knowledge' group. None of them mentioned 'customer' in their responses. The other 27 participants (the 'with prior knowledge' group) had been introduced to the concept of engineering design prior to this course on various occasions, such as an engineering class in high school, Project Lead the Way, Engineering Projects in Community Service High School, Science Olympiad, FIRST Robotics, and through the two design activities in the three day freshman engineering camp at Arizona State University before the fall semester. Four of these 27 participants mentioned customer involvement at the beginning of the process. For example, one of them mentioned "*conduct interviews with those affected by the problem*".

Table 1 shows the frequencies at which this theme was represented in the mid-semester and post-data. The result clearly shows that students' understanding of the importance of customer involvement throughout the design process has greatly improved after the two-week design challenge and has further improved at the end of the course.

Table 1. Customer Involvement in mid-semester data and post-data

	Mid-semester data (Total responses: 63)	Post-data (Total responses: 59)
No mention of customer (percentage of responses)	19.05% (n=12)	10.17% (n=6)
Some mention and involvement of customer in the process (percentage of responses)	44.44% (n=28)	37.29% (n=22)
Extensive involvement of customer throughout the process (percentage of responses)	36.51% (n=23)	52.54% (n=31)

For those who mentioned some involvement of the customer in the process, their responses varied from "*who is the client?*" to "*share it [the design] with whom it may concern*". Most of them showed customer involvement at the beginning stages of the process. Examples of this include "*work with the customer to understand and define the problem*", "*ask the customer questions to better comprehend the requirements, criteria, needs, and wants*", "*work with the customer to prioritize criteria*". A few of them showed that the customer should be involved to validate design solutions before they are finalized, for example, one participant mentioned "*the solution must be checked with the customer to determine validity and effectiveness*".

In responses where extensive customer involvement throughout the process was present, some connected the customer to every step shown in the process while others explicitly annotated how customers can be involved throughout the process, for example, "*consult with [the customer]*", "*ask the customer questions*", "*receive feedback from the customer*". An example concept map for this case is shown below. Quite a few participants mentioned the customer in their written descriptions, for example, "*I created this concept map to help show how important the customer is during the process*", "*In short, my chart emphasizes the need for communication with one's customer throughout the process*", "*The process is centralized around the customer, with their wants and needs influencing the entirety of the project*". These statements show that these participants are more likely to approach design problems using a customer-centric process.

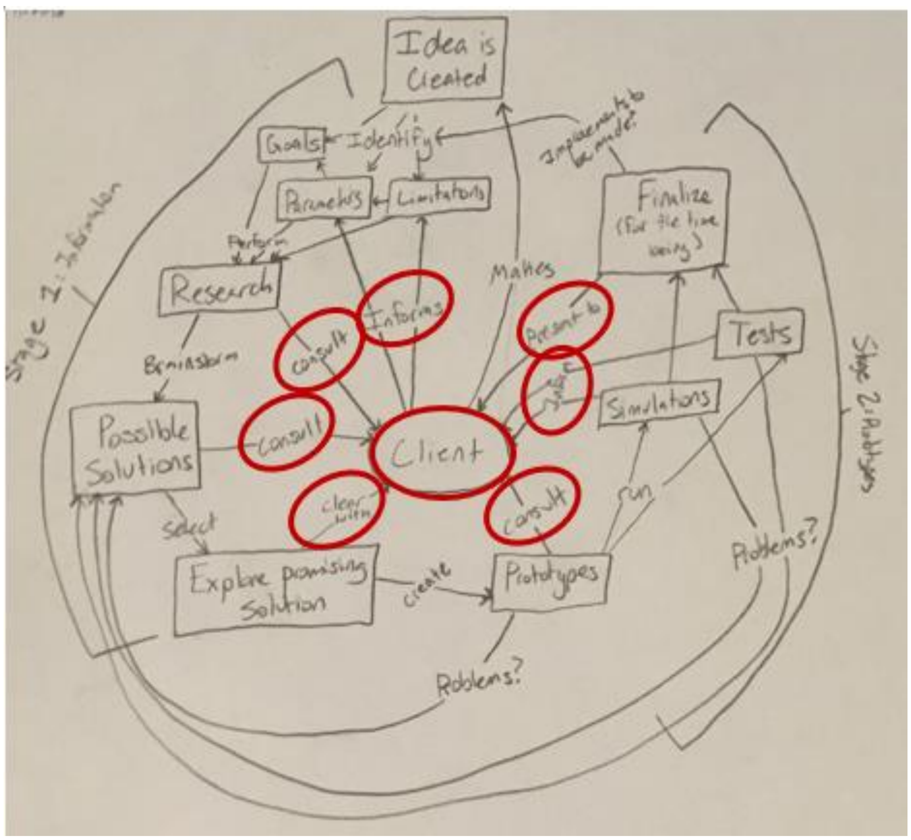

Figure 2. An example concept map that shows the customer involvement throughout the process (relevant elements highlighted)

B. Needs Analysis/Problem Definition

In the pre-data, percentages of participants who showed this theme in their responses are 50% (18 out of 36) for the without prior knowledge group and 55.56% (15 out of 27) for the with prior knowledge group. Almost all of those who showed this theme mentioned "*identify the problem*" without providing any details. Only three responses included some details such as "*understand limitations & parameters*". Only a slight difference was found between these two groups for this theme, indicating that the prior experiences and knowledge did not seem to make a difference in students' understanding.

This theme was found in all but two responses in the mid-semester data and in all responses in the post-data. One participant stated as part of the description, "*In order to effectively use the engineering design process, the problem must be thoroughly explored and include the consumer to get a better understanding of the problem*". In the mid-semester data, 53 out of 63 participants provided specific details and the number is 52 out of 59 for post-data. Examples of specific details mentioned about the theme include "*identify an opportunity to create value for customer*", "*identify the needs and wants*", "*POV [Point of View] statements*", "*think about the main purpose of the design*", "*problem statement*", "*identify key constraints*", "*identify requirements and criteria*", "*rank criteria by importance*". An example concept map that shows specific details for this theme can be found in Figure 3. The results indicate that this course, in particular the two-week design challenge, has been very effective in helping students appreciate the importance of understanding the needs and problem, and establishing parameters such as requirements and criteria before jumping into brainstorming solutions.

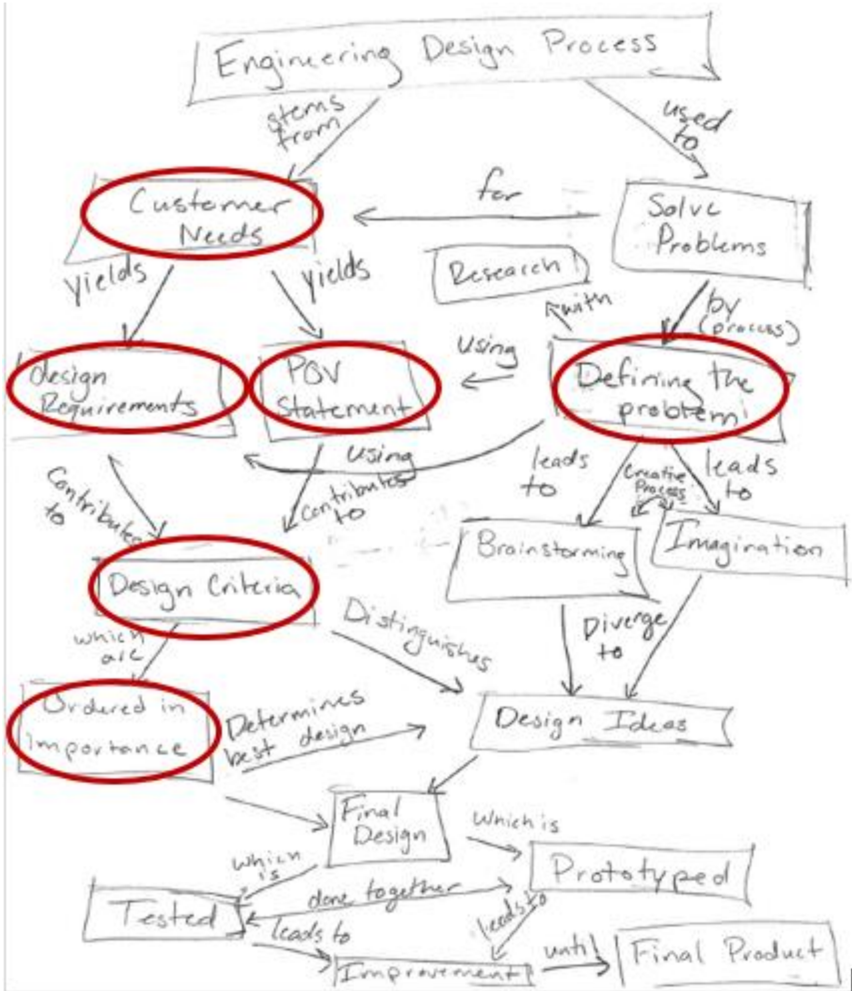

Figure 3. An example concept map that shows specific details for the theme "Needs Analysis/Problem Definition" (relevant elements highlighted)

C. *Other Phases*

Table 2 shows the frequencies at which each of the other phases of the design process was found in the pre-data. Since the results are extremely similar between the with and without prior knowledge groups, when analyzing the mid-semester and post-data, these two groups were not differentiated, and the results for the mid-semester and post-data are shown in Table 3.

Table 2. Theme “Other Phases” found in number of responses in pre-data (Total n=36 for w/o prior knowledge; total n=27 for w/. prior knowledge)

Phases	Pre-data (w/o prior knowledge) # of responses that mentioned the step	Pre-data (w/o prior knowledge) # of responses that mentioned specific details about the step	Pre-data (w/. prior knowledge) # of responses that mentioned the step	Pre-data (w/. prior knowledge) # of responses that mentioned specific details about the step
Research	9	0	9	0
Brainstorm	23	0	21	0
Model/decision making	17	0	8	0
Create	22	0	22	0
Test	15	0	19	0
Improve	11	0	10	0

Table 3. Theme “Other Phases” found in number of responses in mid-semester and post-data (Total n=63 for mid-semester data; total n=59 for post-data)

Phases	# of responses that mentioned this step in mid-semester data	# of responses that mentioned specific details about this step in mid-semester data	# of responses that mentioned this step in post-data	# of responses that mentioned specific details about this step in post-data
Research	32	13	52	29
Brainstorm	58	29	54	32
Model/decision making	59	40	56	51
Create	50	7	54	2
Test	53	16	58	22
Improve	42	0	55	1

For this theme, not much difference is found between the with and without prior knowledge groups in the pre-data, again indicating that the participants' experiences with engineering design prior to this course have not really helped them with a good understanding of it. Multiple gaps still exist in their understanding even though they had been introduced to this concept.

Results in the mid-semester and post-data are quite similar. The major differences were found in phases 'Research' and 'Model'. More participants have mentioned the 'Research' phase and provided details about it in the post-data than in the mid-semester data. This may be due to the fact that the two-week design challenge was mostly done in class and it was about a landmark that most students were familiar with, so not much research was involved in it whereas more research was needed in the ten-week design project. Even though students' understanding about this aspect of the design process has improved throughout the course, majority of them only mentioned one specific way of research, i.e., "*research existing solutions*" and this is considered a weakness in their understanding as multiple modes of information gathering are important [36]. In terms of 'Model', more participants in the post-data have provided specific details such as "*computer simulations*", "*empirical models*", "*scientific and mathematical models*", "*CAD*", "*numerical data*" compared to the mid-semester data. This is probably because that more predictive modeling activities were involved in the ten-week design project.

D. Iterative Characteristic

The pie charts below show the numbers of participants whose design process representations were completely linear and non-iterative, somewhat nonlinear and iterative, and completely nonlinear and iterative. Details of these three categories can be found in the Research Method section.

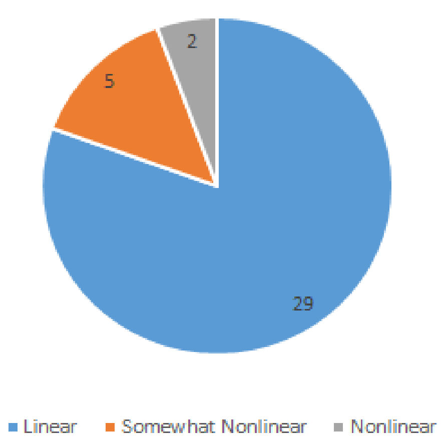

Figure 4(a) Pre-data without prior knowledge

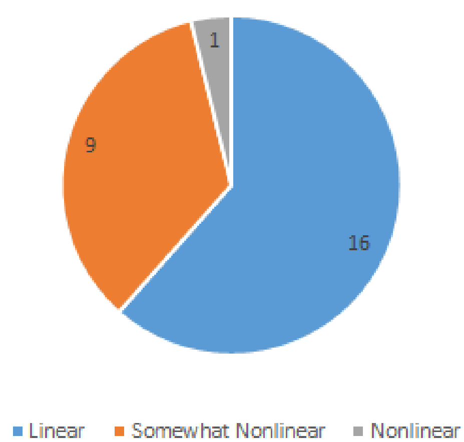

Figure 4(b) Pre-data with prior knowledge

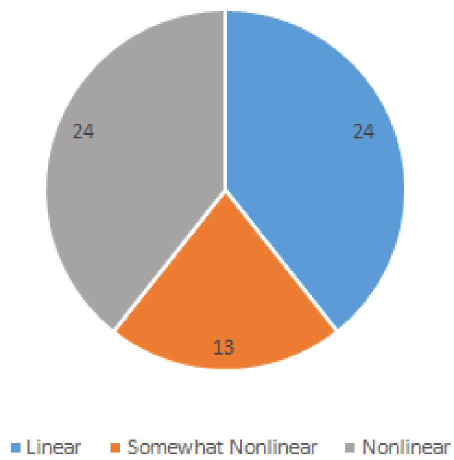

Figure 4(c) Mid-semester data

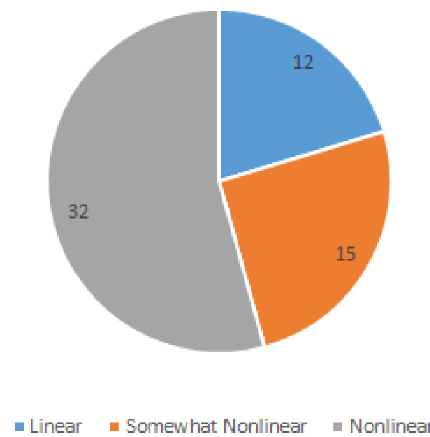

Figure 4(d) Post-data

The results show that students' understanding of the iterative nature of the design process has greatly improved throughout the course. Many of them realized that the process is very fluid by the end of the course. This was validated by the statements found in their written descriptions: "*The process can also jump back to any of the previous points*", "*however, these steps are just a guideline and in reality (due to its iterative nature), steps can be revisited, occur simultaneously, and flow out of order*", "*My concept map shows just how interconnected the steps of the design process are*", "*I drew the engineering design process in a circle because of the fact that it is always continuous. It can always go through the circle again*", "*The engineering process is a fluid structure that allows one to go from anywhere back to the start of a problem*".

Even though great improvement was found in this theme, the fact that about 20% of the participants showed a completely linear design process at the end of the course is concerning. This might be due to the fact that even though iterations were necessary in their ten-week design project, they may have not realized that they were performing design iterations.

E. Complexity of Concept Maps

As discussed in the Research Method section, all the concept maps were grouped into four categories depending on their richness, complexity, and interconnectedness. All of the pre-data responses were found to fall under category 1. The results for mid-semester and post-data are shown in the figure below. Examples of concept maps in each category can be found in Appendix A. It is important to note that the complexity of the concept maps does not directly correlate to the iterative nature of the design process, for example, a concept map might show a completely iterative design process but can still fall under category 1. At the end of the course, all but one student was able to generate a richer and more complex concept map of the design process. The fact that they were able to identify more concepts involved in the design process and links between these concepts is an indicator of an improvement in their understanding. Even though fewer students generated concept maps that fell in category 4 in the post-data compared to the mid-semester data, categories 3 and 4 are considered at a similar level with the only difference being whether relationships between concepts were articulated or not. Though the relationships between concepts are important to note in some cases, such as showing customer's role and involvement in the process, an absence of annotations in other cases is probably not an indicator of a lack of understanding.

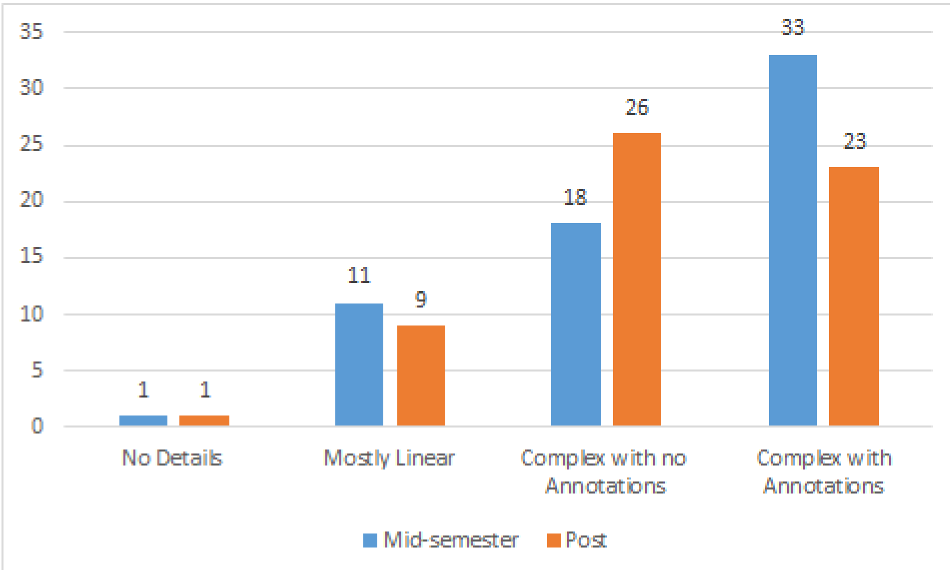

Figure 5. Number of concept maps in each category in the mid-semester and post-data

Conclusions and Future Work

To summarize, through the thematic analysis of the concept maps generated by students three times during the semester in the Introduction to Engineering course, it was found that even though about 43% of the students had been introduced to the concept of engineering design before the course, their understanding of the design process was at a similar novice level in all aspects compared to those who had no prior experiences when entering the course. Their novice level understanding indicates that their prior experiences were probably not in-depth and thus the emphasis of the design process and providing opportunities for students to apply it in order to gain a deeper understanding in the introductory engineering course is vital. In addition, as a result of this course, the majority of the students started to appreciate the importance of customer involvement in the design process. Another finding is that unlike novice designers, at the end of the course all students have realized that needs analysis and problem definition is a phase in the design process that should never be skipped or overlooked. Students' understanding of all the other phases in the design process has also greatly improved throughout the course, especially in the areas of 'Research', 'Model/Decision Making', 'Test', and 'Improve'. A great improvement was also found in their understanding of the nonlinear and iterative characteristic of the design process, though there were still about 20% of participants whose design process representation was completely linear at the end of the course, indicating an area of improvement in the course.

Another weakness in students' understanding was found to be about the 'Research' phase in the design process. Many participants were not able to provide any specific details about this phase at the end of the course, and for those who did provide specific details, their understanding about it is limited to 'research existing solutions'.

As for future work, the authors plan to address the weaknesses found in the course based on results from the data analysis; collect more data to increase the total number of responses; identify and exclude any anomalies in the data for data analysis; define criteria and scores for quantitative ratings of the concept maps and statistical analysis; and perform longitudinal analysis of the three concept maps generated by each individual to better understand changes in understanding of the design process that occur at an individual level.

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Appendix A. Examples of Concept Maps in each of the Four Complexity Categories

The figures below show examples of concept maps in each of the following four categories, respectively, based on their complexity and interconnectedness:

- Category 1: no specific details provided in the concept map
- Category 2: more details are provided but the concept map is mostly linear
- Category 3: more details are provided and the concept map is somewhat complex but relationships between key terms are not articulated
- Category 4: concept map is complex, inter-connected, and connections between key terms are annotated

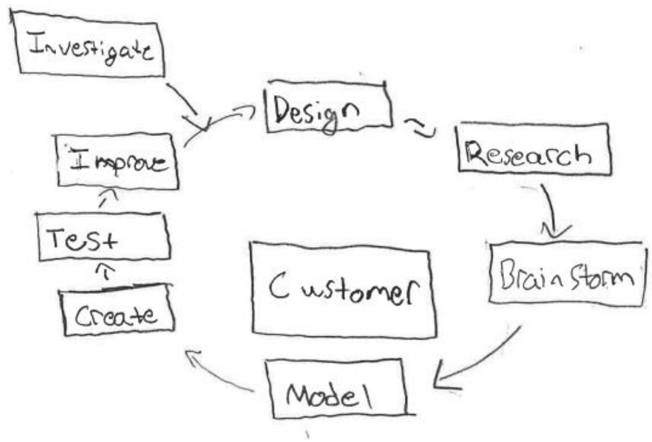

Figure A1. An example of category 1 concept map from the mid-semester data

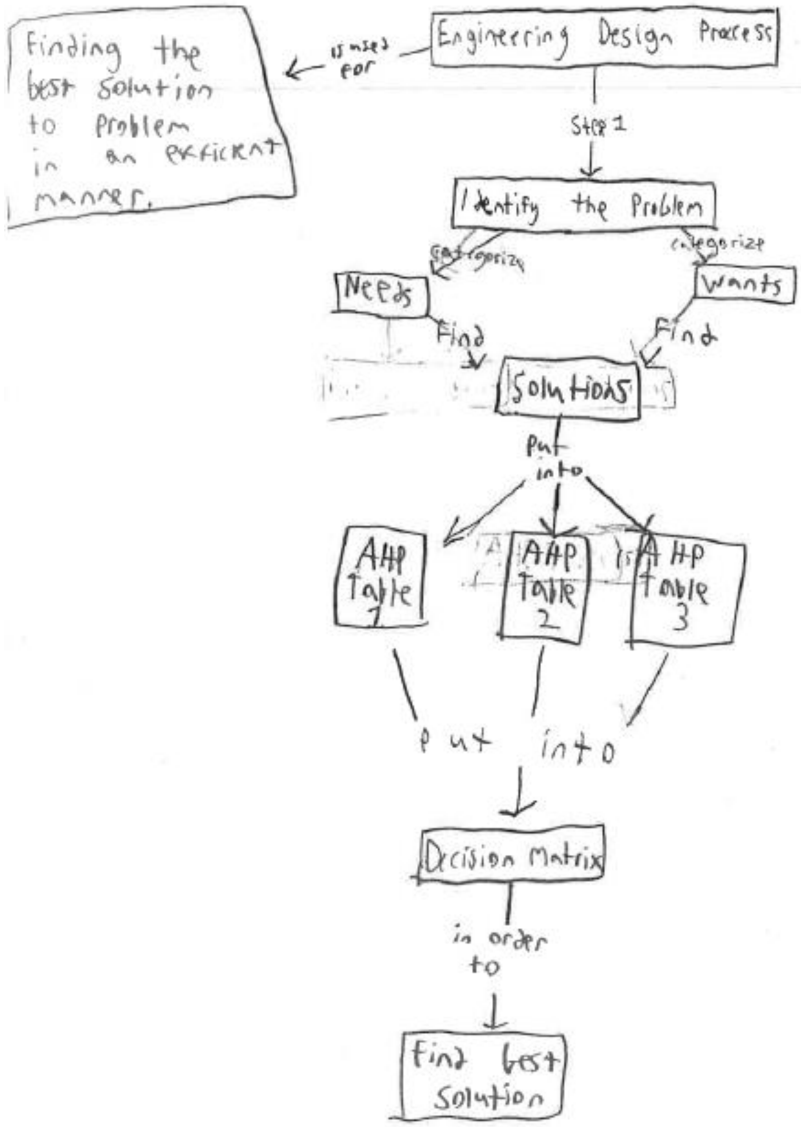

Figure A2. An example of category 2 concept map from the mid-semester data

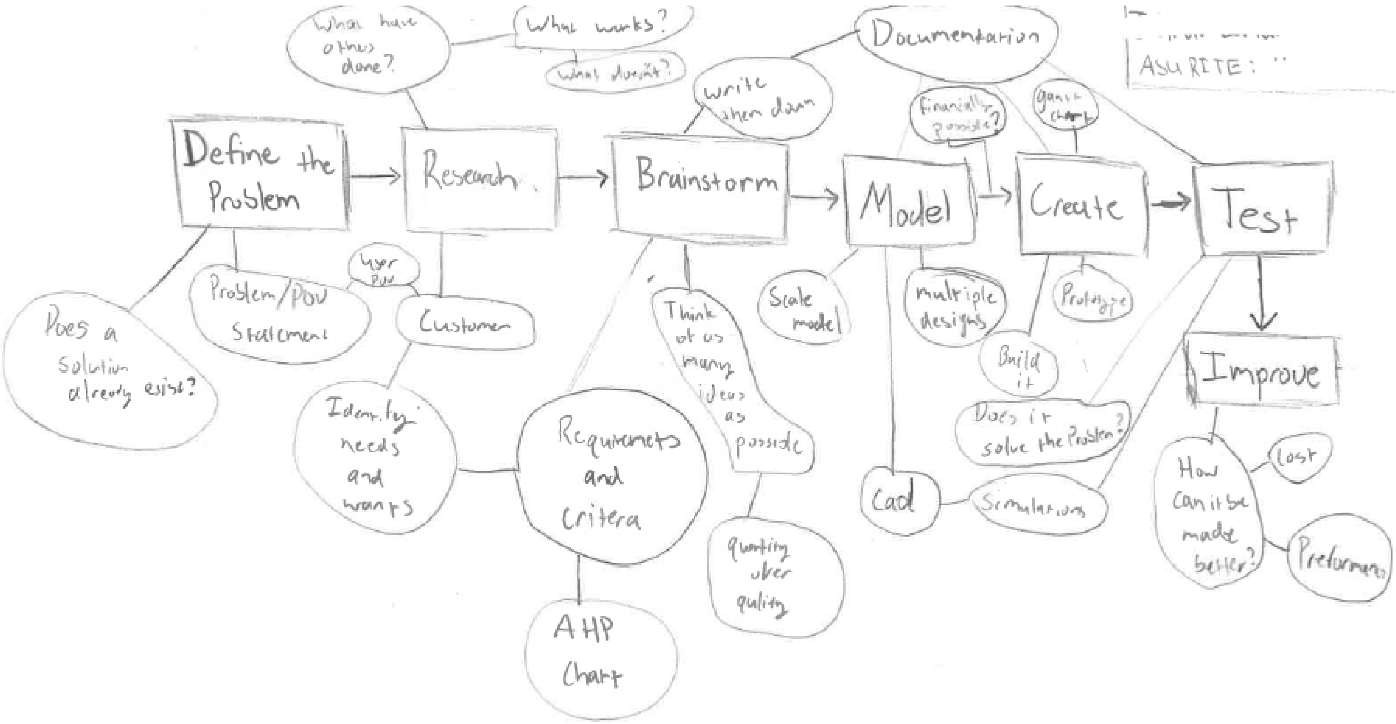

Figure A3. An example of category 3 concept map from the post-data

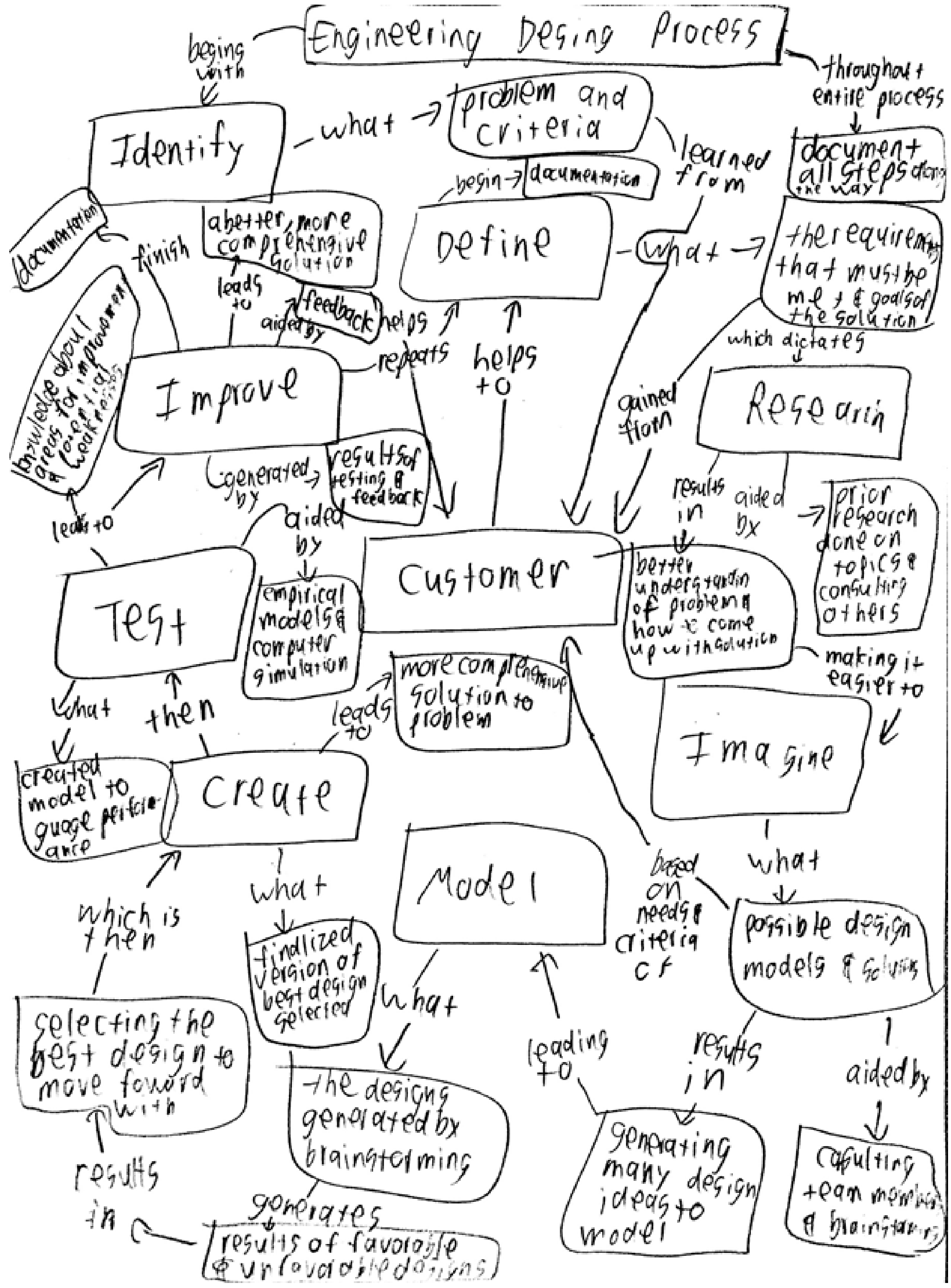

Figure A4. An example of category 4 concept map from the post-data