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RESEARCH ARTICLE

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How do undergraduate engineering students conceptualize product design? An analysis of two third-year design courses

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Abstract

Background: Engineering education traditionally emphasizes technical skills, sometimes at the cost of under-preparing graduates for the real-world engineering context. In recent decades, attempts to address this issue include increasing project-based assignments and engineering design courses in curricula; however, a skills gap between education and industry remains.

Purpose/Hypothesis: This study aims to understand how undergraduate engineering students perceive product design before and after an upper-level project-based design course, as measured through concept maps. The purpose is to measure whether and how students account for the technical and non-technical elements of design, as well as how a third-year design course influences these design perceptions.

Design/Method: Concept maps about product design were collected from 105 third-year engineering students at the beginning and end of a design course. Each concept map's content and structure were quantitatively analyzed to evaluate the students' conceptual understandings and compare them across disciplines in the before and after conditions.

Results: The analyses report on how student conceptions differ by discipline at the outset and how they changed after taking the course. Mechanical Engineering students showed a decrease in business-related content and an increased focus on societal content, while students in the Engineering Management and Industrial and Systems Engineering programs showed an increase in business topics, specifically market-related content.

Conclusion: This study reveals how undergraduate students conceptualize product design, and specifically to what extent they consider engineering, business, and societal factors. The design courses were shown to significantly shape student conceptualizations of product design, and they did so in a way that mirrored the topics in the course syllabi. The findings offer insights into the education-practice skills gap and may help future educators to better prepare engineering students to meet industry needs.

KEYWORDS
concept maps, conceptual learning, engineering design, product design, project-based learning

1 | INTRODUCTION

Historically, engineering curricula have been highly structured and standardized, with required courses in mathematics, scientific theory, and engineering analysis. In many cases, this led to engineering programs that focus on technology and technical theory, with insufficient emphasis on holistic design (Dym, 1999; Froyd & Ohland, 2005; Nicolai, 1998). While these are important concepts for engineers to understand, the needs of modern society require engineered products that take into consideration factors unrelated to technical skills, spanning from user needs to business viability and sustainability (Horváth, 2003). In recent decades, steps have been taken by many colleges and universities to address this issue through initiatives such as project-based learning, engineering design courses, and makerspaces (Chen & Yang, 2019; Howe & Wilbarger, 2006; Wilczynski et al., 2016); however, there still remains a mismatch between engineering students' educational preparation and the real-world demands of new engineers. This knowledge deficit is referred to by many as a skills gap (Brunhaver et al., 2018; Male et al., 2010; May & Strong, 2006; Radcliffe, 2005).

To provide insight into the extent of the current engineering skills gap, the research objective of this study is to explore undergraduate student conceptions of design, how they shift following a project-based design course, and how these conceptions and shifts differ between two degree programs. To date, student conceptions of engineering and engineering design have been studied through a variety of methods, including surveys, text analysis, and concept mapping (Besterfield-Sacre et al., 2004; Cunningham et al., 2005; Dunsmore et al., 2011; Walker et al., 2005). Yet, there is a limited body of literature discussing student conceptions of product design, which this study aims to measure and analyze in a quantitative manner. Three central research questions are explored:

RQ1. *To what extent do undergraduate engineering students' initial conceptions of design account for business and societal contexts?*

RQ2. *In what ways do these design conceptions change after taking a project-based engineering design course?*

RQ3. *How do these design conceptions vary between different engineering disciplines?*

Engineering design is a multifaceted topic, and the breadth of relevant subject matter, along with differences across engineering disciplines, raises challenges in quantifying student perspectives (McKenney & Reeves, 2012). One tool proposed to capture such conceptions is concept mapping, due to its versatility and open-ended structure for eliciting and visualizing an individual's knowledge surrounding a particular subject (Cañas et al., 2005). Concept maps are used in this study to capture student knowledge and mental models around the central idea of *product design*, both at the beginning and end of a semester-long product design course. The term *product design* is used rather than *engineering design* because the former was expected to encourage a more holistic expression of the students' design conceptions rather than limiting them to technical concepts. As the students are enrolled in engineering degree programs and a course sequence about *engineering design*, the resulting concept maps should provide an engineering perspective on the topic of *product design*. The collected concept maps were analyzed for structural and thematic trends, and they were compared across disciplines and between the precourse and postcourse conditions. This allows for an exploratory case-based study of students in these two courses to address the above-stated research questions.

2 | BACKGROUND

This section reviews the current literature surrounding the evolution and teaching approaches of engineering design courses in higher education, as well as the theory and practical uses of concept mapping. These two topics come together in this study to explore engineering design education through concept mapping.

2.1 | Engineering design education

Since the introduction of engineering higher education programs, studies have shown that the distribution of skills in engineers entering industry positions is overly biased toward technical capabilities (Dym, 1999; Nicolai, 1998). This trend conflicts with the original standards set by the American Society for Engineering Education (ASEE), which emphasized the development of engineering graduates with social responsibility through a balance of scientific and humanistic coursework in addition to technical competence (Grinter, 1955). Many industry professionals have reported a skills gap between recent graduates and the workforce requirements, resulting in difficult transitions into the workforce (May & Strong, 2006). Some of the highlighted shortcomings of recent engineering graduates include market context understanding, communication, and independent learning (Gewirtz et al., 2018). The skills gap seemingly stems from different levels of historical prioritization in engineering design education between universities and industry (Dym, 1999; Nicolai, 1998). This increases initial industry costs for recent university graduate hires, as they need more extensive training and additional workplace experience to reach an acceptable level of professional preparedness. Engineering colleges and universities have recognized these education deficits by surveying what industry professionals are looking for in recent graduates, and in the last two decades, they have sought to offset this gap by finding ways to incorporate design coursework into their curricula (Back & Sanders, 1998; Todd et al., 1995).

Several new approaches to teaching engineering design have been proposed and implemented to expand the curriculum beyond the theoretical and technical core concepts to an application-focused, holistic approach (Sanders, 2012). Teamwork, communication, business and market context, problem-solving, and project management are emphasized more heavily in design courses than in other areas of engineering curricula, giving university graduates the professional context they need for their technical skills. With the goal of closing the skills gap and better preparing their students for the workforce, universities are motivated to emphasize and improve their design programs (Sheppard & Gallois, 1999). Most design courses share similar goals; however, universities vary in their approaches to implementing design education.

Capstone projects have become a common and effective tactic to enable students to apply knowledge in design-focused tasks that emulate industry engineering processes (Howe & Wilbarger, 2006). Capstone projects give students the opportunity to take on an independent project from the idea phase through completion. Other engineering design education approaches have been proposed to bring more context into the full undergraduate curriculum. The conceive, design, implement, and operate (CDIO) approach offers a full restructuring of engineering education, reprioritizing complementary additions to the technical aspects of engineering design as requirements in order to promote a more holistic approach (Crawley et al., 2014). The CDIO approach was designed with the input of companies who hire engineering graduates to prepare them to move into positions of leadership, placing emphasis on management and entrepreneurial thinking (Crawley et al., 2011). A similar approach is integrative STEM education, an interdisciplinary approach to teaching students science, technology, engineering and mathematics (STEM) topics that seeks to improve understanding by providing context to these subjects (Sanders, 2012).

Many of these pedagogical approaches include the increasingly popular project-based learning, which pairs course lessons with a parallel project that is related to a real-world context (Mills & Treagust, 2003). Project-based learning applies elements of the constructivism philosophy, with the idea "that learning is more engaged when triggered by a student's 'I need to know' than by a teacher's 'because you should know'" (Chen & Yang, 2019, p. 71; Lenz et al., 2015, p. 68). A large-scale meta-analysis of the effects of project-based learning, focusing on 12,585 university students in Eastern Asia and the Americas, found that project-based learning had a medium to large positive statistical effect on students' academic achievement (Chen & Yang, 2019). It is important, however, to note that project-based learning is implemented in diverse ways, including variances in project duration, complexity, topic, specialization, and team size.

These approaches and techniques tend to emphasize interdisciplinary learning and project-based learning to better prepare engineering students for their careers. However, these pedagogical methods have not been universally implemented, and their impacts on student conceptualizations of design have not been systematically studied. The present study investigates the impacts of project-based courses on student conceptualizations of design.

2.2 | Concept mapping

A concept map is an educational tool that acts as a visual representation of key concepts surrounding a topic and the meaningful relationships among those concepts (Novak & Gowin, 1984; Walker & King, 2003). An example of a concept map surrounding the central idea of product design is shown in Figure 1. Concept maps are comprised of nodes, typically circled or boxed terms that represent individual concepts, and edges, typically arrows tying concepts together with a linking phrase that represents the connection between the nodes, illustrated in Figure 2. While there are various types of concept maps—for example, they can be hierarchical or nonhierarchical, or free-form or highly structured—this basic composition of concepts and links remains the same (Davies, 2011).

Concept maps, founded in the research of educational psychology, were first created to reflect the main principles of Ausubel's assimilation theory of meaningful learning, which states that the assimilation of knowledge into previously developed knowledge structures is the most effective way to learn (Ausubel, 1968). The map itself functions to represent one's current network of knowledge surrounding a topic. As one's understanding of a broad topic expands, new nodes are incorporated into the network. As explained in a metacognitive study of concept mapping, the "gestalt effect" of concept maps allows for all of one's ideas to be together as one whole, connected network. This can help students identify gaps in their knowledge and form new connections (Schwendimann, 2015).

The simple structure of concept maps as networks of nodes and links mirrors the psychological structure of semantic memory (Wandersee, 1990) (Amin et al., 2014). Storing information in semantic memory involves connecting concepts through a hierarchy of broad, encompassing categories that branch off into increasingly specific terms that relate to one another (Collins & Quillian, 1969). Therefore, similar to the way that an outline exists to represent the logical flow of information surrounding a topic, a concept map exists to represent the flow of information as it is stored as semantic memory (Wandersee, 1990). As a result, concept maps have a unique ability to represent and visualize the connections that exist in the human brain.

However, there are varying theories regarding how these maps activate memory, with two major schools of thought. One is dual coding theory, which states that there are two distinct ways to encode verbal and nonverbal responses (Clark & Paivio, 1991). This theory asserts that concept maps encode information into visuospatial memory, while

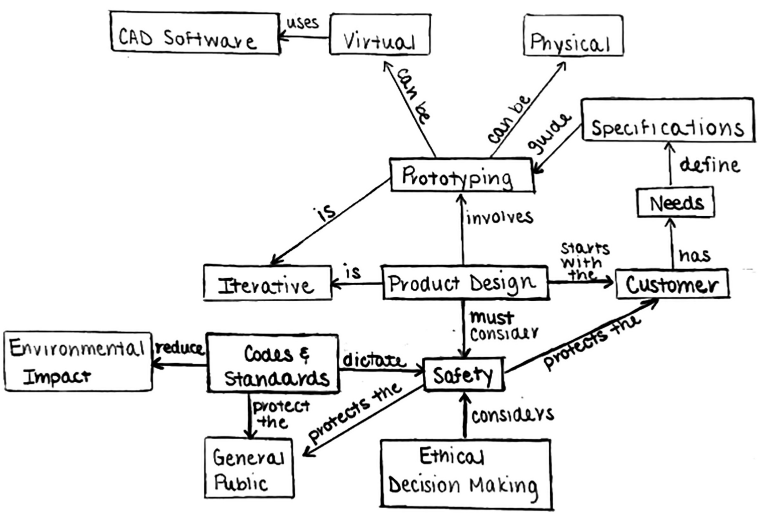

FIGURE 1 Example concept map around the central theme of product design

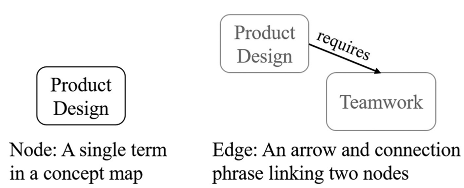

FIGURE 2 Example of concept map node (left) and edge (right)

more traditional methods such as lecturing encode information into verbal memory. Therefore, targeting both forms of memory is believed to boost understanding (Kalhor & Shakibaei, 2012). In contrast, verbal coding theory contends that concept maps do not activate visuospatial memory, but they do activate verbal memory in a unique way. Under this theory, concept maps facilitate verbal coding by connecting concepts with similar meanings (Nesbit & Adesope, 2006). Both of these schools of thought see the value of concept maps as a unique way to boost understanding and represent connected concepts. Moreover, studies have found concept maps to be effective at visualizing top-level concepts over minute details (Amadieu & Salmerøn, 2014; Nesbit & Adesope, 2006).

For the broad topic of *product design* of interest in the study reported here, concept maps were selected as an appropriate tool for gaining insight into the general themes that students associate with the topic. Other assessment methods were also considered for the study, such as graphic organizers in the form of lists and tables, written essays, multiple-choice questions, and think-aloud activities. Concept maps held several advantages over these alternatives, including their documented abilities to engage participants in critical thinking, capture complex thought processes, and simultaneously collect a large number of responses (Fonteyn, 2007; Gil-Garcia & Villegas, 2003).

2.2.1 | Educational studies

Concept maps have been used in a variety of educational contexts. Two common educational uses of concept maps are assessing student knowledge and capturing knowledge from students and experts. Concept maps are just one of many classroom tools used to assess student knowledge. In a study of students in a science class learning about chlorofluorocarbons (CFCs), concept maps were constructed by the students and compared to a teacher's master map (Rye & Rubba, 1998; Schvaneveldt, 1990). Through associative network analysis, a configurational similarity index was found for each student's map in comparison to the master map, and their knowledge was assessed based on this measure of similarity. They found that by comparing the concept mapping results to other measures, like performance in interviews, there was evidence of the validity of using concept maps in this way as a tool for assessment.

Researchers have also looked into the learning value of concept mapping activities. Two meta-analyses of the literature concluded that concept mapping exercises—particularly when students construct concept maps themselves—have positive effects on learning, particularly in helping students develop critical thinking skills, connect theory and practice, and enhance academic performance (Machado & Carvalho, 2020; Schroeder et al., 2018). Recent studies compared the effectiveness of different concept mapping activities for their learning value, including reviewing static concept maps, translating static maps into paragraph form, filling in missing concepts within partially defined maps, and filling in missing labels within partially defined maps (Wang et al., 2021; Wong et al., 2021). Their knowledge was then assessed through open-ended and multiple-choice questions after the activities. The exercises with the fully defined static maps led to higher performance than those with the partially defined maps. The authors attributed this to the students' low levels of prior knowledge on the topic, and they also suggested that the act of translating knowledge facilitates meaningful learning better than fill-in-the-blank exercises.

Many studies have explored the impacts of classroom implementations of concept mapping. One such study took place in a high school physics course, where students were provided terms on slips of paper and asked to arrange them. The students' knowledge was then assessed by structural components, numbers of links and connectivity, and the number of "good links" that had previously been identified by experts (Austin & Shore, 1995, p. 43). Another study investigated a year-long biomedical engineering design course and compared expert maps to student maps; both the organization and the content of student concept maps were analyzed to show that between the beginning and end of the course, the gap between the experts and students had narrowed (Walker et al., 2005). The major differences between experts and students, even at the end of the course, were in the areas of marketing and societal concerns. In the field of industrial engineering, a concept mapping study assessed student understanding of engineering using both traditional network analysis methods (e.g., number of nodes and edges) and a holistic approach with experts rating the maps based on a set of criteria and using this to create a rubric (Besterfield-Sacre et al., 2004). Fang (2018) incorporated eight concept mapping exercises throughout an engineering dynamics course, and after each one, the instructor selected the best maps to share and discuss as a class. An end-of-course survey found that more students agreed than disagreed that the concept mapping was a positive experience and helped improve their conceptual understanding. Another study applied Novak and Gowin's (1984) scoring method to find significant differences in their students' learning before and after an advanced accounting course, which was validated by a significant improvement in test scores (Chiou, 2008).

In other scenarios, concept maps have been used to visualize the information in one's brain surrounding a certain topic. One study that included both cross-sectional and longitudinal studies of biomedical engineering students focused on capturing their understanding of their major. It was found that at the end of the course, their precision of language and structural organization improved (Walker & King, 2003). Another study similarly attempted to capture the understanding of biology students surrounding their conceptions of life zones in the ocean. One group was provided with 45 min of computer-aided learning about this subject, while another group was provided learning on a different topic. The concept maps were used to measure the complexity of both student groups' knowledge on the subject; they found that the concept maps of the experimental group showed increased complexity while the control group did not (Wallace & Mintzes, 1990). Hu et al. (2019) used neuroimaging to measure cognitive resources used during a concept mapping exercise in the context of grand challenges in sustainability. They found that subjects undertaking the concept mapping exercise generated more concepts and had lower cognitive loads than subjects undertaking a similar concept listing exercise.

There has also been an increase in online concept mapping tools being developed for student use. To address a lack of constructivist-based collaborative learning environments, CmapTools was created (Cañas et al., 2004). This technology was unique in that it allowed for student collaboration and discourse surrounding one anothers' maps, supporting the idea that there is no single ideal concept map. Another study chose to create and test a different concept mapping software to help young students organize information when searching online (Hwang et al., 2014). The results showed that the concept mapping approach could enhance problem-solving. Both of these studies found benefits in organizing student conceptions through the use of their respective tools.

2.2.2 | Assessment methods

Concept maps are generally quantitatively assessed in either an absolute sense, when the evaluators know what makes a concept map correct, or a comparative sense, when the similarities or differences between samples are of interest. They can also be qualitatively assessed to explore the presence or absence of themes. For a broad, multidisciplinary topic like product design (the topic of the present study), even academic experts do not have a common understanding of its definition or scope (Simpson et al., 2008). This raises challenges in evaluating concept maps in an absolute, quantitative manner, as there is no expert consensus regarding the most important terms or connections in a concept map about product design. In this setting, concept maps can instead be used to portray students' thought processes as they change over time and become more adept in the subject (Walker & King, 2003). While student understanding of specific course material can be extrapolated from concept maps, the focus of this study is not to objectively assess the quality of the students' understanding of product design. Rather, the maps are used to qualitatively explore the presence of different broad topics, as well as the quantitative and qualitative conceptual changes between different groups of students and before and after their participation in a semester-long product design course.

3 | METHOD

This research takes a quantitative, case-based, comparative approach to address the research questions posed in Section 1. The study involved the collection and quantitative analysis of concept maps to understand students' initial conceptions of design, cross-disciplinary comparisons, and precourse and postcourse changes in the context of two project-based undergraduate engineering design courses.

3.1 | Theoretical framework

This study is guided by the constructivism framework. This model contrasts with the traditional view that there is an objective truth that can be directly passed from teacher to student (Bodner, 1986). Rather, the theories of constructivism state that knowledge is actively constructed in the human mind and that each student creates different knowledge structures to fit their understanding of the world (von Glasersfeld, 1995). This suggests that knowledge is structured and understood differently in each person's mind. Studies have shown that engineering students do not lack scientific and technical knowledge upon entering the workforce (Nicolai, 1998); however, applying these types of knowledge to practical situations is a point of weakness (Kolari & Savander-Ranne, 2000). The principles of constructivism demonstrate a need for engineering programs to integrate professional practices into the classroom to combat this issue (Duffy & Cunningham, 1996; Newsletter & Svinicki, 2014).

The constructivism framework aligns with this study's goal to better understand how students conceptually acquire and organize their knowledge, building on several theoretical foundations in engineering education research. One of these is the understanding that students' conceptions of product design are constructed in their undergraduate engineering courses, specifically in project-based design classes (Dym et al., 2005). This implies that a more comprehensive understanding of how students construct their knowledge in these classes can provide insights into how that knowledge can be applied to situations in professional life. This led to the first research question that investigates students' initial conceptions of design. Furthermore, since students in different degree programs have different technical interests and are exposed to different specific content in their curricula, the third research question compares students at similar stages in two different undergraduate disciplines.

Another key theoretical foundation for this study is derived from Ausubel's theories of meaningful learning and assimilation (Ausubel, 1968). These state that learning is most effective when new information is related to prior knowledge. This implies that by integrating more contextual information into engineering design courses, students will assimilate this information into their pre-existing knowledge structures. The second research question investigates the differences between student conceptions before and after the courses to explore how project-based engineering design courses change students' conceptions of product design.

In order to capture the varying and nuanced conceptions that each student holds, a broad, open-ended educational tool was required. Founded in constructivism and Ausubel's theories of meaningful learning, concept mapping was identified as a suitable way to elicit and measure these student conceptions (Bodner, 1986). Concept maps reveal how students have encoded learned material into memory (Kalhor & Shakibaei, 2012; Wang et al., 2021), and collecting maps at the beginning and end of a project-based course can uncover these internal structures and their changes, providing insights into all three research questions described in Section 1.

3.2 | Course context

This study was conducted at Stevens Institute of Technology, a private university in the northeastern United States, with approximately 3500 undergraduate students, most of whom study engineering disciplines. The engineering curricula at Stevens all include an eight-course Design Spine sequence, aligning with the eight semesters of a traditional 4-year degree. The first five Design Spine courses are standard across all engineering and engineering-related disciplinary majors. These design courses are all project based, with a heavy focus on specific design fundamentals such as mechanics, circuits, and materials. In the sixth semester, the design fundamentals are then applied in major-specific design courses to prepare the students for a year-long senior design project that spans the seventh and eighth semesters (Sheppard & Gallois, 1999).

This study analyzes students enrolled in the sixth course of the Design Spine: Design VI. This is the first course in which all of the aspects of engineering design learned in the previous semesters are synthesized and applied in one project-based course, emphasizing design as a process. In the Mechanical Engineering (ME) course, students develop a ping-pong ball launcher that is meant to both work technically and meet the needs of the market. The Engineering Management (EM) and Industrial and Systems Engineering (ISE) students, who are taught in one combined section, choose their own projects based on their interests, where the main requirement is that it must result in a physical consumer product. In both courses, the project is referenced in each lesson to give context to the Design VI material. Since the projects were conducted in teams and in a small number of closely related product domains, the team project contents were not included in the analysis of individual concept maps.

Design VI was chosen for this study, particularly in the ME and EM/ISE programs, because it is the only course at Stevens Institute of Technology that primarily focuses on design as a process, bringing other engineering content together in a project-based learning experience. Both the ME and EM/ISE courses are grounded in broad mechanical design theory, focus on the design of physical products, and use the same textbook, *Product Design and Development* (Ulrich et al., 2020). While the sections had different instructors, and the specific course topics slightly varied between the ME and EM/ISE courses, the objectives of these two Design VI courses were similar in their aims to promote holistic perspectives, processes, and techniques for product design.

TABLE 1 Design VI course learning objectives by discipline

Mechanical Engineering	Engineering Management/Industrial and Systems Engineering
• Characterize the product design process as a structured problem-solving activity	• Familiarize with different methods and tools in technical design and appropriately apply them to develop, analyze, and select design solutions
• Define a problem statement, establish design constraints, and justify design decisions	• Assess the expected performance of designs within the appropriate context and criteria
• Plan a design project	• Apply engineering principles and analysis tools to solve complex design problems
• Create, evaluate and select design concepts	• Explore different presentation styles and practice communicating ideas and project progress through written assignments and oral presentations
• Conduct detailed design with CAD software (e.g., SolidWorks)	• Discuss and evaluate design- and systems-related issues that impact today's society and the engineering, design, and management needs within it
• Plan prototyping and testing	• Facilitate team projects by managing team members, scheduling, and deliverables throughout the semester
• Apply design rules for material selection, design for manufacturability, design for assembly	• Experience working within teams and honoring individual commitments to the team
• Recognize issues of product safety, risk, and reliability	• Demonstrate the steps involved in taking a product from conception to market through a course project

Including two different versions of this course allows for comparisons that investigate differences between student populations with different background knowledge and interests, as well as different specific curricular elements. Furthermore, the ME course has a larger student population to enable statistically significant findings, while the EM/ISE course includes additional qualitative data collection through weekly student reflections (described later), which provides insights into some of the students' thought processes. The curriculum differences can be seen in the learning objectives in Table 1 and the weekly course topics in Table 2. In general, the ME sections focus on more of the engineering technical elements of the design process, with weekly topics like geometric dimensioning and tolerancing, while the EM/ISE section places more emphasis on market research, management, and communication.

One key difference between the two courses was the incorporation of a market simulator as a design support tool. This simulator was developed specifically for engineering design education and allowed students to test their potential products in a simulated market to see how successful the product is against competitors (Hoffenson & Fay, 2021). The simulator was tightly integrated into the EM/ISE course, with an hour-long class session devoted to its use, along with follow-up of individual written reflection assignments and team project reporting requirements. To examine whether the simulator alone might have an influence on design conceptions, half of the ME students were also introduced to the simulator through a 1-h in-class exercise, but no follow-up exercises were assigned to this group.

As an integral part of the course, the EM/ISE curriculum included weekly individual reflection assignments, where students wrote weekly 300- to 500-word reflections about specific topics covered in class that week. Reflective learning has been utilized in problem-based curricula to teach students professional skills and how to self-critique their work (Williams, 2000). Reflection allows students to slow down and think through situations, enabling self-directed learning, encouraging metacognition, and helping students make sense of complicated situations (Moon, 2001). Of particular interest to this study is the Week 15 reflection, which asked students to reflect on their concept maps and how they changed between precourse and postcourse. The insight into students' thoughts in these Week 15 reflections adds context to the concept map data.

3.3 | Positionality statement

The author team—comprised of individuals of various backgrounds, experiences, career stages, research interests, and expertise—are connected by their motivations to explore the influence of course design and content delivery on student learning of design concepts. The first, second, third, and fourth authors have close ties to the institutional context: The

TABLE 2 Design VI weekly course topics by discipline

Week	Mechanical Engineering	Engineering Management/Industrial and Systems Engineering
1	Intro to product development, development processes, and organizations	What is design?
2	Identifying customer needs, product specifications, quality function deployment	Engineering/systems design models and challenges
3	Concept generation and selection	Leadership, teamwork, and personal styles
4	Concept testing and project management	Problem definition and system boundaries
5	No class	Market research and the voice of the customer
6	Product architecture	Concept generation and creativity
7	Geometric dimensioning and tolerancing	Selecting the best concept
8	Proposal presentations	Communication
9	Rapid prototyping	Midterm presentations
10	Design for environment	Detailed design and optimization
11	Design for manufacturing and assembly	Prototyping, testing, and validation
12	Codes and standards	Production and economics
13	Engineering ethics, patents, and intellectual property	Business planning
14	Industrial design	Design reviews
15	Final presentations	Final presentations and reflections

first and third authors completed all of the courses in the Design Spine as undergraduate students, while the second author was, at the time of data collection and analysis, a first-year undergraduate student who had not yet taken the Design VI course. The fourth author has taught the EM/ISE Design VI course for six semesters, including the EM/ISE course section in this study. The sixth and seventh authors are engineering education researchers and have conducted several research studies aimed at exploring how classroom activities and course design influence how students develop disciplinary and conceptual knowledge over time. The fifth author is an undergraduate Mechanical Engineering student who, at that time, had completed several design courses but had not taken part in the Design Spine.

In designing and conducting this study, each member brought to the work a constructivist perspective guided by their belief that learning is more meaningful when students actively engage in the process. As a whole, the team applied this lens to design the data collection method, analyze the data, and report the findings. Using their knowledge of the content, context, and engineering education research broadly, the authors were able to infer the changes in the participants' conceptions of design as they engaged with the course content and class activities.

3.4 | Data collection

Participants were recruited using convenience sampling among the students enrolled in the ME and EM/ISE Design VI courses, spread across five course sections. As ME is a more popular discipline, four of these sections were ME (referred to as Sections A–D, containing 109 total students) and one was a combined EM and ISE section (Section E, with 23 students: 20 EM and 3 ISE). Sections A and B were taught by one instructor, Sections C and D were taught by a second instructor, and Section E was taught by a third instructor. However, it is important to note that all of the ME sections used the same syllabus, lecture slides, and assignments. In the ME sections, 19% of the students identified as female and 23% as non-White, which is typical of national engineering gender demographics, but less diverse in terms of ethnicity (Roy, 2019). In the EM/ISE section, 43% of the students identified as female and 35% as non-White, which is more aligned with national ethnicity demographics but more gender-balanced than is typical (Roy, 2019). After signing an informed consent document, each participant was instructed to complete a concept map during class time, at the beginning and the end of the course. However, 25 students from Sections A–D and two students from Section E did not complete both maps, so the set of participants for the precourse to postcourse comparisons was reduced to 105. The consent procedure and data collection plan described in this section were approved by the Stevens Institute of Technology Institutional Review Board (IRB) under protocol 2017–016 (20-R1).

The precourse concept maps were collected during the first week of the course. As all students may not have been familiar with concept maps, the students were first given a brief tutorial on concept mapping, using examples in other domains, and a class-wide group concept map generation exercise around the topic of personal health. In the tutorial, the students were instructed that: (i) all concepts should be framed as nouns or noun phrases that represent events, objects, or characteristics; (ii) all links should be represented as one-way arrows with linking phrases so that they can be read in natural language as concept-link-concept; and (iii) all concepts included should be linked in some way to the network of concepts. The students were then given 15 min to draw their precourse concept maps surrounding a central node of product design, using the following prompt:

> 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).

The 15-min time frame was chosen after the instructor pilot tested an in-class concept mapping exercise with a class of 32 students during the previous semester. The pilot test participants broadly agreed that 15 min was the most suitable amount of time for generating concept maps. This was confirmed during the precourse concept map data collection in the present study, where the instructor observed that most students had stopped or slowed substantially by the 15-min time limit. Moreover, the instructor specifically asked the students for feedback on the timing immediately after the precourse concept maps were completed, and none indicated a desire for more time.

During the final 3 weeks of the semester, each section was presented with a brief reminder of concept map structures, and then the same prompt was used to collect postcourse concept maps. It should be noted that this semester was disrupted by the COVID-19 pandemic, and the courses moved from in-person during Weeks 1–7 to online after that. Therefore, while the precourse concept maps were generated live on paper in the classroom, the postcourse concept maps were generated live on paper during a virtual class session. In the postcourse instance, the students uploaded scans or photographs of their concept maps. The instructions were the same in both instances, asking the students to spend the full 15 min on the exercise, but the postcourse results rely more heavily on trust in the students since it was impossible for the research team to observe the amount of time actually spent working on the maps.

Additional data were gathered from the EM/ISE students, who completed weekly reflections on the material they had learned. In Week 15, after completing the postcourse concept maps, the students were instructed to write a 300–500 word reflection for the following prompt:

> Write about what has changed about your conceptual model of engineering design since the beginning of the semester. For reference, look back at your reflections and concept maps from the beginning and end of the course.

These reflection assignments were not assigned to the ME students, as reflections were not a weekly part of the ME Design VI course and are, therefore, not a primary focus of this article. However, key themes and patterns from the reflections were identified and are summarized in the discussion. These qualitative data were consulted to provide self-reported explanations and reasonings behind the results found in the quantitative analysis.

3.5 | Data analysis

Prior to data analysis, each participant was assigned a unique ID for anonymity, and their precourse and postcourse maps were digitized into a spreadsheet. An edge-based verbal coding technique was used for digitizing the concept maps, where the researchers manually entered each source term and target term in pairs for every edge connection drawn by the participants. This allows the maps to be analyzed by their layout structure, the content included in the nodes, and the relationships included as edges (Nesbit & Adesope, 2006).

Structural and content analyses were performed on all of the collected concept maps. The three research questions posed in the introduction were addressed, respectively, by (1) assessing the thematic content of the precourse concept maps, (2) analyzing the changes between the precourse and postcourse concept maps, both structurally and thematically, and (3) evaluating the differences between the students in the ME and EM/ISE sections. A combination of statistical tests and measures of effect size were used to evaluate the significance of all quantitative findings.

3.5.1 | Structural analysis

The structural analysis quantifies how the students formatted their concept maps. This provides insight into how the knowledge they included in their map is organized in their minds (Wandersee, 1990), focusing on the layout of the map rather than the content of the nodes. This is similar to an approach taken by a previous study that analyzed within-subject concept maps related to sustainable development (Segalás et al., 2008). The approach includes analyzing the number of nodes, the number of edges, and the network density, which is the number of edges as a percentage of the number of potential edges if all node pairs were connected (Borgatti & Everett, 1997). For example, the concept map in Figure 1 contains 14 nodes (concepts), 17 edges (one-way arrows), and a density of 0.093 (17 total edges as a fraction of 182 total possible edges). These metrics provide insights into the breadth and depth of student understanding of both product design as a whole and specific themes related to product design. Some research suggests that a concept map with a higher density of edges per node represents a complete understanding of the theme (Walker & King, 2003). After digitizing the concept map contents, the number of nodes and edges were totaled for each student. These totals were averaged and compared by section and discipline.

3.5.2 | Content analysis

The content analysis investigates the terms students chose to include in their maps. This provides insight into the breadth and depth of their knowledge surrounding a specific topic (Novak & Cañas, 2006). To begin to understand the changes in content between the precourse and postcourse maps, the specific word occurrences were counted and compared between the two sets of data. One master list of terms was generated for all of the collected concept maps, and then comparisons of term occurrences and frequencies were made between the disciplines and the precourse and postcourse conditions. The master list was made before any analysis was completed to limit researcher bias. It was anticipated that keywords and ideas specifically taught in the course would be among the terms that had the largest increases in frequency.

Each unique concept was assigned to thematic and subthematic categories to understand how the subject matter of concepts generated by the students changed. Each concept on the master list of terms was manually categorized into an evolving list of common themes and subthemes present. This sorting was checked and revised multiple times by the entire research team until a consensus was reached. This process is similar to Rye and Rubba's (1998) method, which included the creation of a rubric of 140 predetermined terms relevant to physics upon assessing student maps.

Previous literature has varied on whether to utilize fewer larger categories or many specific categories when analyzing terms in a broad engineering topic such as product design. In Horváth's (2004) analysis on the current state of engineering design research, nine different groupings were used, including human assets, design knowledge, and design theory. Others specifically studying product design used broader thematic groupings, such as people, business, and technology (Stappers et al., 2007). By combining these two strategies, this analysis includes three overarching themes to categorize the data: *Engineering*, *Business*, and *Society*, as well as an *Interdisciplinary* category for terms spanning all three (e.g., *product* and *design process*) and a *Generic* category for terms with no discernable standalone meaning (e.g., *everything* and *yes*). Note that italic text is used in this article to denote both thematic categories that begin with capital letters and verbatim terms from concept maps that are represented in lowercase. For example, the term *product design* was placed into the *Generic* category since it was given to the students as the central node and is, therefore, not representative of original student thought. Terms classified as *Generic* were excluded from the analysis as they do not offer meaningful insights about thematic content. Subthemes were included under each of the three top-level themes to analyze the interactions among more specific concepts. The final list of themes and subthemes is shown in Table 3. At the end of the sorting process, each term, excluding *Interdisciplinary* and *Generic* terms, was categorized into exactly one theme and one subtheme.

After the concept map terms were categorized into themes and subthemes, the data were analyzed in different ways to holistically capture each student's submission. For each map, the number of nodes per theme and subtheme was divided by the total number of terms to calculate a percentage of terms in each category. Using a percentage instead of

TABLE 3 Three major themes and their four respective subthemes in final node categorization

Engineering	Business	Society
Technical skills	Finance	Government and citizens
Conceptual development	Market	Sustainability
Prototyping and testing	Operations	Ethics
Manufacturing and production	Project management	Standards and codes

a raw number of average occurrences eliminates potential bias toward concept maps with more nodes. The mean of these percentages was calculated by section and discipline for statistical analysis.

A similar process was used to compare the content of the courses themselves to the content found in the student concept maps. The objectives of each course detailed in the syllabi (Table 2) were categorized into predetermined themes from the thematic and subthematic analyses. The number of objectives per theme was then divided by the total number of objectives to provide the thematic and subthematic composition percentage for each syllabus. These percentages were compared to the average student percentages calculated in the previous analysis to explore potential correlations between the two.

Finally, the interconnectivity of each map, more specifically the cross-theme connections, were measured. Interconnectivity looks at how frequently nodes in one theme connect to nodes in a different theme rather than to another node within the same theme. Links between different branches of knowledge often suggest creative thought in the map producer, represented by connecting two different areas of knowledge and integrating them together (Novak & Cañas, 2006). In response to this principle, an interconnectivity analysis was performed on edge pairs to observe all created node combinations. These cross-theme connections were calculated as percentages per map, similar to the overall thematic analysis described previously.

3.5.3 | Significance and effect size

Before any statistical tests were conducted, the distributions of quantitative metrics were analyzed by shape, measures of center, and measures of spread. This allowed for an assessment of normality or possible skewnesses that could disrupt the data. Next, t-tests were performed to investigate statistically significant differences between the structural and thematic content analyses. With each student providing both precourse and postcourse concept maps, the data were paired by the student and compared with a matched two-tailed t-test. Three standard levels of significance were assessed (p-values at or below 0.05, 0.01, and 0.001) and are indicated in all reported results.

In addition, effect size as measured by Cohen's d was calculated to measure the strength of the changes between the precourse and postcourse maps and between disciplines. For the differences between the precourse and postcourse maps, Cohen's d for matched data, using the standard deviation of the differences, was calculated. For the differences between disciplines, the standard Cohen's d, using the pooled standard deviation, was calculated. Standard measures of effect size indicate different amounts of change. Cohen's d rule of thumb has been used to interpret the effect sizes, with 0.2 indicating small effect size, 0.5 indicating medium effect size, and 0.8 indicating large effect size (Cohen, 1988). The rule of thumb effect size values are similar to other effect sizes found and used in previous education-focused concept mapping research; one concept mapping meta-analysis determined that effect sizes lower than 0.491 are small, and those greater than 0.491 are large (Nesbit & Adesope, 2006). The rule of thumb was chosen in this study to provide three levels of granularity in effect size classifications. The p-values and Cohen's d values combined allow for discussions about the significance and strength of the changes between the precourse and postcourse data and the differences between the disciplines.

3.6 | Limitations

The scope of this study involves a number of assumptions, leading to inherent limitations in the results. First, the participants were selected based on enrollment, and therefore the sample size was constrained, particularly in the EM/ISE group. Additionally, the students were all from a single institution and just three engineering degree programs, which are unique due to the Design Spine sequence. Because of Stevens' unusual program structure, the results may not be representative of a broad range of students' experiences or backgrounds; however, they may serve as a basis for comparison for future studies. Furthermore, the data collection did not gather any background information directly from the participants, which may have limited the analysis by not being able to study the impacts of factors such as demographics or previous academic or industry (e.g., internship and co-op) experience. Aggregate demographic information was instead collected from the institution without the ability to map characteristics to individual participants. It should also be noted that the students were involved in other engineering courses at the time that may have influenced their conceptual models, and this study is unable to disentangle learning that took place specifically in the Design VI course.

The results are also contingent on the idea that concept maps are representative of student knowledge. Because this study did not involve any substantive modifications to the course syllabi, only concept maps were collected at two specified time points in the semester. If more data had been collected, either through additional concept maps or other course assessments, opportunities would have been available to triangulate learning or validate the measured changes in student knowledge. Such additional data collection would also help researchers to develop a more comprehensive understanding of the changes in student design conceptions. Finally, since no expert consensus exists regarding which elements and connections should be included in a concept map of product design, the findings may only be analyzed in a comparative sense within the collected data, with no way to evaluate the quality of concept maps in an absolute sense other than through inferences based on the syllabus.

4 | RESULTS

The structure, content, and relationships captured in the concept maps were measured and compared between disciplines and between the precourse and postcourse submissions. As this is an exploratory, case-based study, no specific hypotheses are posed. Rather, the analysis aims to understand initial design conceptions, as well as in what ways these two courses influenced design conceptions.

While the ME students had nearly identical curricula, there was one difference between Sections A and B and Sections C and D. Sections A and B of the ME students included a 1-h class session in which the students were introduced to a market simulator (described in Section 3.2) and allowed time to use it to explore their projects' marketability, whereas Sections C and D did not include that session. However, the statistical comparisons between Sections A and B and Sections C and D structurally, thematically, subthematically, and intercategorically showed no significant differences in the precourse data or postcourse data; this indicates that the 1-h exercise early in the semester, lacking any follow-up assignments, was largely ineffective in influencing the students' conceptualizations of product design. Therefore, the analyses presented in this section are broken up by discipline, with all ME sections treated as one homogeneous group.

4.1 | Structural analysis

Structural analysis of network characteristics, including numbers of nodes, edges, and density, are frequently used when quantitatively evaluating or comparing concept maps or groups of concept maps (Austin & Shore, 1995; Besterfield-Sacre et al., 2004; Segalás et al., 2008; Walker et al., 2005). The structural analysis revealed significant changes between the precourse and postcourse concept maps in the number of nodes and network density, shown in Table 4. In both cases, the ME students showed significant changes, with the number of nodes increasing with a small effect size and the network density decreasing with a medium effect size from precourse to postcourse. Between the disciplines, the ME students had fewer nodes and higher densities than the EM/ISE students in their precourse concept maps, but these differences were not statistically observed postcourse.

4.2 | Terminology changes

In addition to the number of nodes, the frequency of occurrence of specific nodes in the precourse versus postcourse maps was also recorded. Terms that increased and decreased the most were broken down by discipline and compiled into the lists in Tables 5 and 6. The nodes that increased tended to be more specific terms or phrases such as *concept*

TABLE 4 Structural analysis metrics; averages and statistical comparison results using *t*-tests and effect sizes, compared by discipline (rows) and precourse versus postcourse (columns).

	Precourse average	Postcourse average	*p*-value (pre vs. post)	Cohen's *d* (pre vs. post)
Nodes				
ME	15.96	18.80	< .001***	0.407
EM/ISE	20.62	21.67	.527	0.140
p-value (ME vs. EM/ISE)	.003***	.122		
Cohen's *d* (ME vs. EM/ISE)	0.912	0.409		
Edges				
ME	21.57	21.67	.921	0.011
EM/ISE	25.67	25.14	.783	−0.061
p-value (ME vs. EM/ISE)	.050	.093		
Cohen's *d* (ME vs. EM/ISE)	0.563	0.440		
Network density				
ME	0.105	0.075	< .001***	−0.641
EM/ISE	0.070	0.067	.807	−0.054
p-value (ME vs. EM/ISE)	< .001***	.393		
Cohen's *d* (ME vs. EM/ISE)	−0.787	−0.195		

Abbreviations: EM/ISE, Engineering Management/Industrial and Systems Engineering; ME, Mechanical Engineering.
Notes: Statistical significance levels: * $p < .05$; ** $p < .01$; *** $p < .001$.

TABLE 5 Difference between precourse and postcourse term occurrences in Mechanical Engineering sections; terms with highest increases (left) and decreases (right)

Term	Total	Term	Total
consumer needs	32	*idea*	−33
manufacturing	28	*user*	−31
concept selection	27	*product*	−30
concept generation	25	*problem*	−24
specifications	22	*technology*	−20
alpha prototype	19	*solution*	−19
ethics	18	*research*	−17
iteration	15	*marketing*	−16
beta prototype	13	*redesign*	−16

generation, *market research*, and *alpha prototype*. The nodes that decreased the most were often more general terms such as *product*, *idea*, and *technology*.

To investigate to what extent terms were commonly used by the students, the number of instances of specific terms in the groups of concept maps were investigated. Table 7 shows slight increases from precourse to postcourse for all participant groups, meaning that more students were using the same terms. However, a two-sample *t*-test assuming unequal variances revealed that these changes are statistically insignificant, and the effect sizes are also very small.

4.3 | Thematic analysis

After the terms were classified into themes and subthemes, statistical comparisons of the categorical frequencies in the precourse versus postcourse maps were performed, provided in Figures 3–6. Possibly due to the larger number of ME

TABLE 6 Difference between precourse and postcourse term occurrences in Engineering Management/Industrial and Systems Engineering section; terms with highest increases (left) and decreases (right)

Term	Total	Term	Total
surveys	15	*product*	−8
market research	14	*user needs*	−6
concept generation	12	*time*	−5
prototype	11	*innovation*	−5
concept selection	8	*idea*	−4
market simulation	8	*technology*	−4
brainstorming	7	*solution*	−4
competition	6	*cost*	−4
pugh matrix	5	*money*	−4

TABLE 7 Number of instances of individual terms in concept maps; average (avg.) and standard deviation (std. dev.) by discipline, with statistical comparisons between precourse and postcourse

	Precourse	Postcourse	*p*-value	Cohen's *d*	Term count
	avg. (std. dev.)	avg. (std. dev.)	(pre vs. post)	(pre vs. post)	(pre vs. post)
Total	2.96 (6.65)	3.04 (7.04)	.766	0.011	667 (679)
ME	2.84 (5.95)	2.91 (5.05)	.850	0.013	472 (553)
EM/ISE	1.77 (2.01)	2.08 (2.88)	.123	0.126	244 (221)

Abbreviations: EM/ISE, Engineering Management/Industrial and Systems Engineering; ME, Mechanical Engineering.
Notes: Statistical significance levels: * $p < .05$; ** $p < .01$; *** $p < .001$.

students, more statistically significant differences are observed in that group than in the EM/ISE students. As shown in Figure 3, the ME students' postcourse concept maps consisted of proportionally more *Engineering* and *Society* terms and fewer *Business* and *Interdisciplinary* terms than in the precourse maps. This indicates that, during the course of the semester, the ME students internalized proportionally more *Engineering* and *Society*-related terms into their conceptual understanding of product design. The only statistically significant thematic change in the EM/ISE population was a decrease in *Interdisciplinary* terms.

4.4 | Subthematic analysis

Each of the 12 subthemes, shown in Figures 4–6, naturally contains fewer terms than the broader themes, and they vary substantially in size. The largest subtheme, *Conceptual development*, contains approximately 23% of terms in the postcourse maps, while the smallest, *Government and citizens*, contains just 0.35% of terms. However, analyzing at the subthematic level reveals internal significant changes not seen at the thematic level. For example, this is seen within the EM/ISE students, who significantly decreased in *Technical skills* terms in Figure 4 but not enough to affect the overall *Engineering* theme in Figure 3. The ME students are seen to increase in every *Engineering* subtheme, with statistically significant increases in *Technical skills* and *Prototyping and testing*.

Within the *Business* subthemes, shown in Figure 5, the trends were different between the disciplines. For the ME students, terms within the *Business* theme declined across all subthemes, with significant changes in three of the four: *Finance*, *Market*, and *Project management*. In contrast, EM students nearly doubled in *Market* terms; this change had the study's only recorded large effect size of 0.830. These contrasting changes mark a divergence in thought between the two disciplines and demonstrate the effectiveness of an EM/ISE curriculum designed with a stronger emphasis on business management and market-driven design.

Despite an overall decrease in *Business* terms, ME students tended to focus more on *Society* than their EM/ISE counterparts, as shown in Figure 6. Along with dedicating a larger portion of their maps to societal terms, ME students

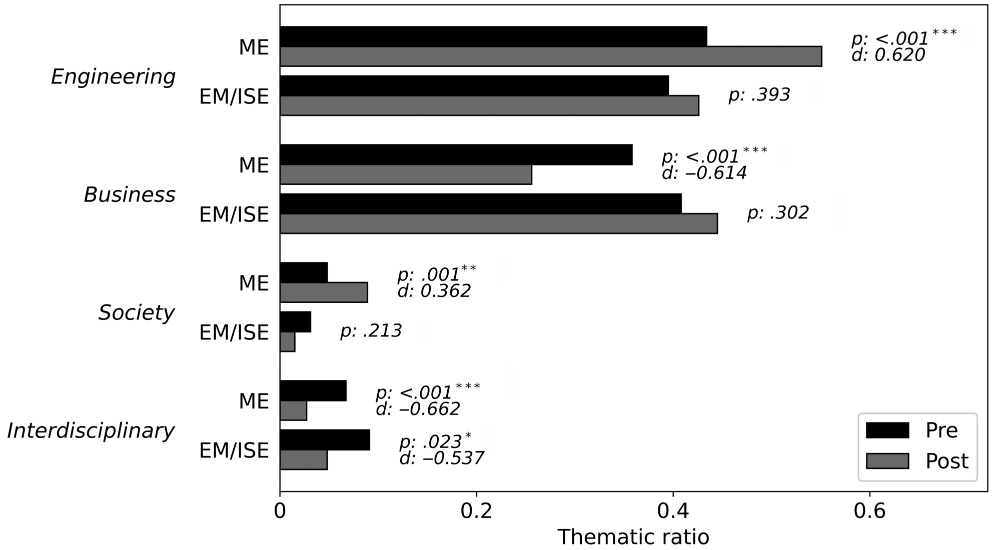

FIGURE 3 Average percentages of thematic terms in each discipline, Mechanical Engineering (ME) and Engineering Management/Industrial and Systems Engineering (EM/ISE), with statistical results from t-tests (p-values) and effect size (Cohen's d) comparing precourse to postcourse changes; asterisks represent statistically significant p-values: * $p < .05$; ** $p < .01$; *** $p < .001$.

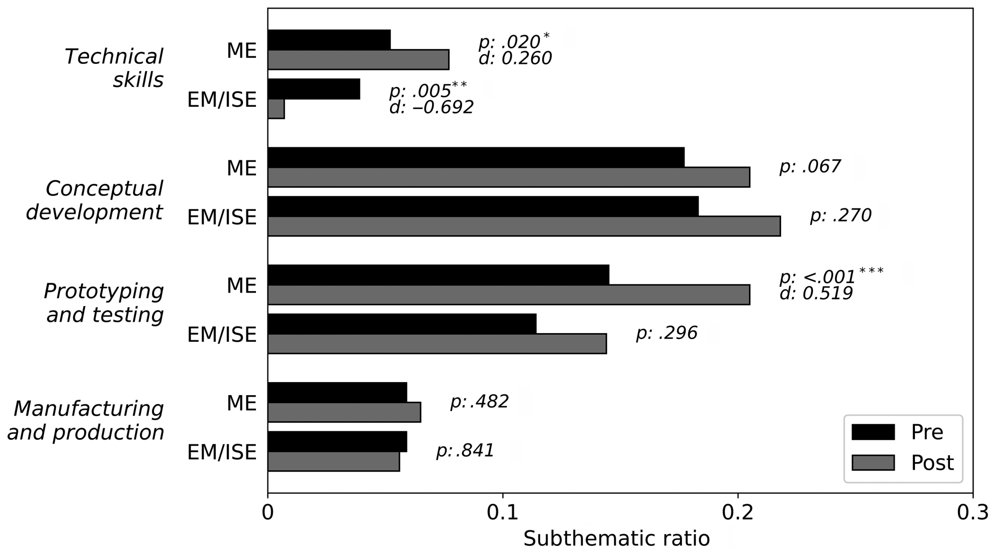

FIGURE 4 Average percentage of terms within *Engineering* subthemes in each discipline, Mechanical Engineering (ME) and Engineering Management/Industrial and Systems Engineering (EM/ISE), with statistical results from t-tests (p-values) and effect size (Cohen's d) comparing precourse to postcourse changes; asterisks represent statistically significant p-values: * $p < .05$; ** $p < .01$; *** $p < .001$.

displayed a significant increase in 3 of the 4 *Society* subthemes: *Sustainability*, *Ethics*, and *Standards and codes*. The EM/ISE students, on the other hand, saw a significant decrease in *Society* terms. This difference in thought is supported by the differences between the two syllabi of the courses, see Table 2. ME topics included design for environment, codes and standards, and engineering ethics, while none of the EM/ISE weekly topics specifically highlighted societal themes.

The correlations between the thematic elements of the concept maps and the themes of the topics covered in each Design VI discipline are shown in Figure 7. Here, the course topics were categorized from the week-by-week schedules in their respective syllabi, and they were normalized to be represented as a percentage of all weekly topics. In almost all cases, the course topic percentage shifted the precourse to postcourse concept map contents in the same direction, with the lone exception of the EM/ISE *Business* topic.

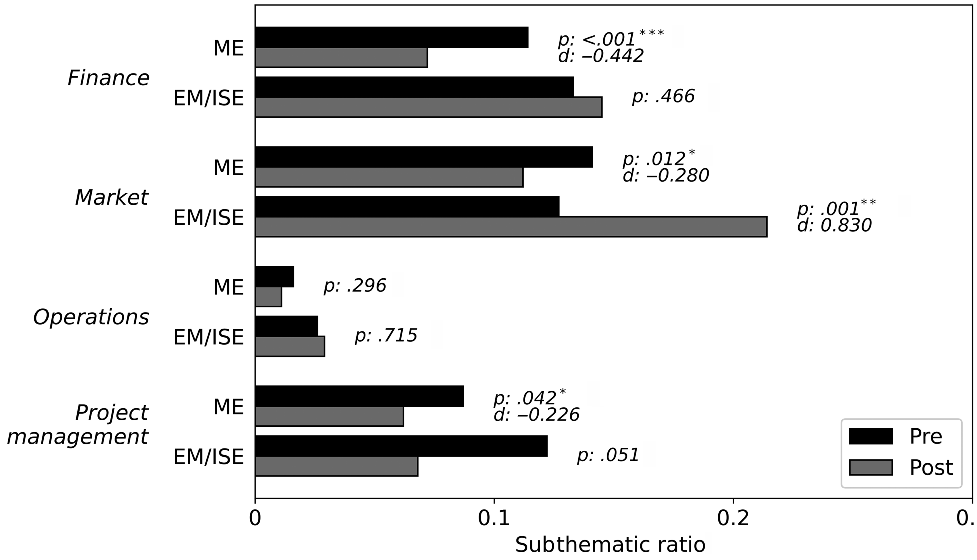

FIGURE 5 Average percentage of terms within *Business* subthemes in each discipline, Mechanical Engineering (ME) and Engineering Management/Industrial and Systems Engineering (EM/ISE), with statistical results from t-tests (p-values) and effect size (Cohen's d) comparing precourse to postcourse changes; asterisks represent statistically significant p-values: * $p < .05$; ** $p < .01$; *** $p < .001$.

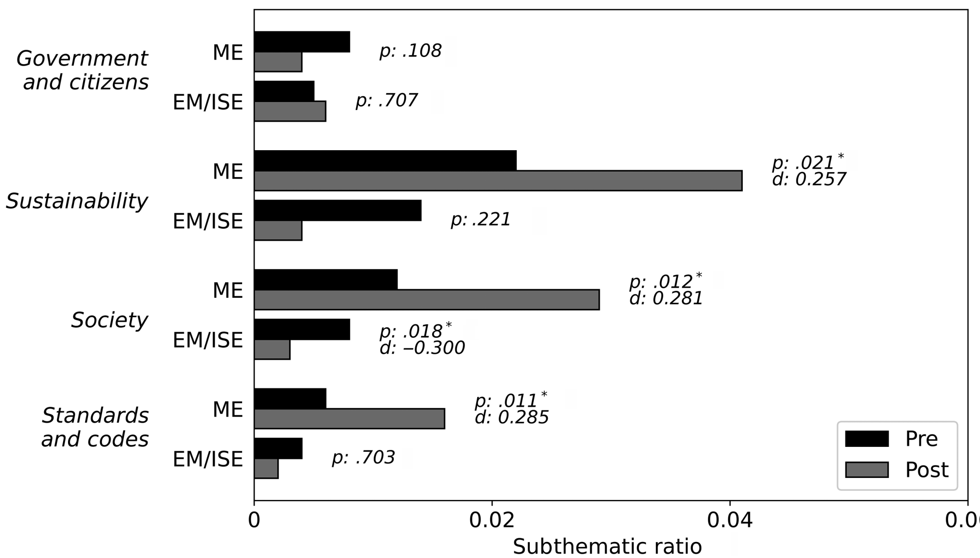

FIGURE 6 Average percentage of terms within *Society* subthemes in each discipline, Mechanical Engineering (ME) and Engineering Management/Industrial and Systems Engineering (EM/ISE), with statistical results from t-tests (p-values) and effect size (Cohen's d) comparing precourse to postcourse changes; asterisks represent statistically significant p-values: * $p < .05$; ** $p < .01$; *** $p < .001$.

4.5 | Thematic interconnectivity

For examining the interconnectivity of the themes in the individual concept maps, a cross-theme analysis was performed to examine how many of the edges connect terms from different themes. Table 8 shows the percentage of edges that connect two nodes of different themes in the top section labeled "all nodes." For example, if an *Engineering* node is connected to a *Society* node by an edge in the concept map, that would be considered a cross-theme edge, whereas an edge connecting two *Engineering* nodes would not be a cross-theme edge. The other elements of the table are the percentages of specific interconnection combinations, such as *Business-Society*. Over the span of the course, the percentage of cross-theme edges decreased in both disciplines. This corresponds with the decreases in density observed in Table 4 but also may indicate higher clustering of related terms in the postcourse concept maps.

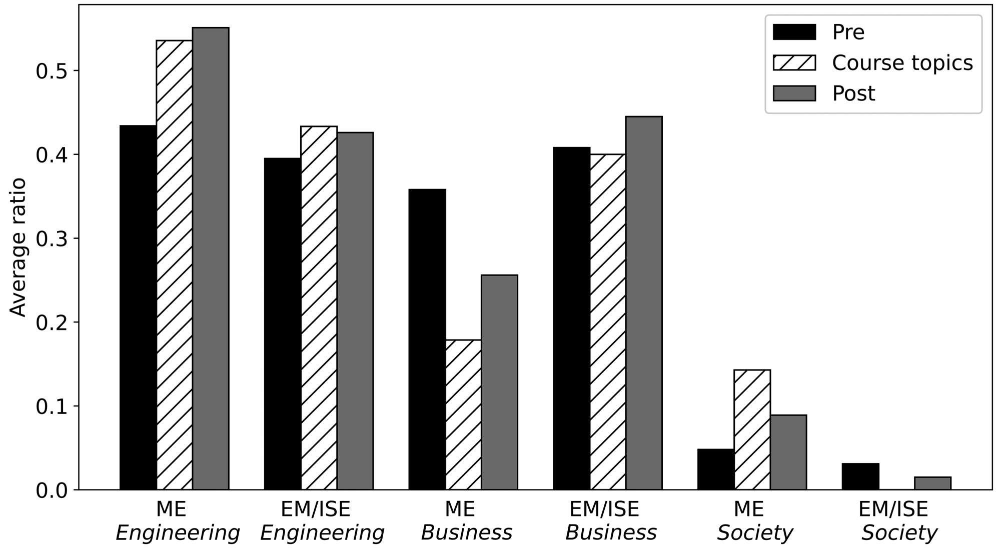

FIGURE 7 Percentage of thematic terms in precourse and postcourse concept maps alongside percentages of weekly course topics that fall into those themes, by discipline, Mechanical Engineering (ME), and Engineering Management/Industrial and Systems Engineering (EM/ISE).

Specifically, *Engineering-Business* connections decreased, and *Engineering-Society* increased among the ME students. No significant changes were found between *Business-Society* connections. Significant changes were found linking *Interdisciplinary* nodes with *Engineering*, *Business*, and *Society* nodes; all were found to significantly decrease except *Business-Interdisciplinary* connections and *Society-Interdisciplinary* connections among the EM/ISE students.

5 | DISCUSSION

The results provide insights into the three research questions of the study. The first research question, regarding students' initial conceptions of design, is addressed through the thematic analysis and discussed in Section 5.1. The second question, about the changes between precourse and postcourse student assessments, is discussed from structural and thematic perspectives in Sections 5.2 and 5.3, respectively. The third research question investigates the differences between the ME and EM/ISE students and is addressed as appropriate in all three of these sections. Finally, the findings of the study lead to practical and theoretical implications for teaching and research, discussed in Sections 5.4–5.6.

5.1 | Precourse student conceptions

The precourse concept map analysis address the first research question: To what extent do undergraduate engineering students' initial conceptions of design account for business and societal context? The results of the thematic analysis shown in Figure 3 demonstrate that in the precourse concept maps, students considered the business context nearly as much as they considered the engineering aspects of design, with approximately 40% of terms in their maps dedicated to each of these themes. This was found across disciplines, as no statistically significant differences were found between ME and EM/ISE students. However, the societal context was lacking at the beginning of the semester for both ME and EM/ISE students: Only five percent of precourse concept map terms fell under the *Society* theme. This illustrates a low emphasis on the societal impact of product design in earlier engineering courses. However, as there is no standard for how much engineers should be considering these business and societal contexts, no definitive conclusions can be drawn about how these results translate to the education-practice skills gap.

The structural analysis showed more contrasts between the ME and EM/ISE students' precourse conceptions. In general, EM/ISE students presented more concepts with a lower density of connections than the ME students. The similarity in content and contrast in structure implies that at the beginning of the Design VI course, ME and EM/ISE students' knowledge surrounding product design was approximately the same, but this knowledge was organized in their

TABLE 8 Percentage of cross-theme edges in each group, averages and statistical results from *t*-tests and effect sizes between precourse and postcourse

	Precourse	Postcourse	*p*-value	Cohen's *d*
All nodes				
ME	0.329	0.257	< .001***	−0.532
EM/ISE	0.338	0.283	.005***	−0.594
Engineering-Business				
ME	0.188	0.144	.002***	−0.345
EM/ISE	0.180	0.205	.359	0.205
Engineering-Society				
ME	0.026	0.052	.002***	0.342
EM/ISE	0.019	0.012	.421	−0.179
Engineering-Interdisciplinary				
ME	0.053	0.030	.008***	−0.295
EM/ISE	0.072	0.026	.007***	−0.656
Business-Society				
ME	0.019	0.018	.825	−0.024
EM/ISE	0.020	0.007	.177	−0.306
Business-Interdisciplinary				
ME	0.038	0.013	< .001***	−0.466
EM/ISE	0.046	0.033	.456	−0.166
Society-Interdisciplinary				
ME	0.005	0.000	.008***	−0.298
EM/ISE	0.001	0.000	.329	−0.218

Abbreviations: EM/ISE, Engineering Management/Industrial and Systems Engineering; ME, Mechanical Engineering.
Notes: Statistical significance levels: * $p < .05$; ** $p < .01$; *** $p < .001$.

minds differently. This may be interpreted as EM/ISE students exhibiting more attention to breadth, or wider arrays of concepts, while ME students are more focused on depth, with a smaller number of topics that are more tightly connected. It is unclear whether this is due to a predisposition to breadth or depth in these respective student populations or whether other non-Design Spine courses in the discipline-specific curricula prepared the students to think in these ways.

5.2 | Changes in structure and terminology

Some studies suggest that, since concept maps represent one's knowledge structure, an increase in the number of terms in a map indicates an increase in knowledge (Novak & Gowin, 1984). Following this understanding, a significant increase in average nodes would suggest significant student learning from the beginning to the end of the course. While ME students showed a significant increase in terms, EM/ISE students did not significantly change structurally. Previous studies have also theorized that cross-theme links and more connected knowledge structures are also indicators of higher levels of understanding about a topic (Novak & Cañas, 2006). With significant decreases in network density and interconnectivity in both ME and EM/ISE students, as seen in Tables 4 and 8, this interpretation would suggest that the students in this study exhibited a decrease in their understanding of product design from the beginning to end of the semester.

However, additional evidence suggests that students in both disciplines refined their understandings of product design throughout the course. For example, the terminology analysis showed an increase in domain-specific vocabulary taught in the course. Tables 5 and 6 show the differences in frequency of terms from the precourse maps to the postcourse maps by discipline. All of the words and phrases in the left columns that increased the most are specifically taught in their respective Design VI sections. These results support the idea that the students are using more precise language to describe their ideas surrounding product design, including vocabulary specifically used in their respective courses. As a result, the use of more general terms decreased, as seen in the right columns of Tables 5 and 6. The terms that decreased the most from the precourse to postcourse maps were generally broader terms, such as *product*, *idea*, and *technology*. This decrease in general terms is further supported by the decrease in terms from the *Interdisciplinary* theme of broad-encompassing terms. These findings are aligned with previous concept mapping research that found increases in the precision of language (Walker & King, 2003).

In addition, the decreased variation of the terms shown in Table 7, although slight, further illustrates a convergence of ideas within the participants in each course. The average number of term occurrences increased across the board from precourse to postcourse maps, including for all students and by discipline. This means that the terms used in the postcourse maps were mentioned by more students on average than in the precourse maps, thus showing a decrease in term variation. The results of these analyses suggest that student conceptual models of product design were substantially refined as they progressed through the Design VI course, either through comprehension of the material taught or through memorization and recall of repeated terms, despite the fact that they did not exhibit higher raw numbers of nodes or connections between nodes.

Due to the contradictory results of the structural and terminology analyses, the authors explored the qualitative data gathered to gain a more thorough understanding of the concept maps and to explore the reasoning behind the patterns discovered. Specifically, the Week 15 reflections provided such insights about the EM/ISE students. A common trend found in these reflections was students commenting that their postcourse maps were more organized, structured, and well thought out. One student wrote:

> While looking at the old concept map I drew, it seems to lack a flow of order. The map appears to be more of a web, and wildly connected. The diagram has many things that are factored into product design, but ultimately has no structure .... In my personal opinion my second concept map did a far better job of accomplishing this.

Another student explained their inclusion of fewer terms and connections, stating:

> Although there is less volume in the end of semester concept map in comparison to the Week 1 map, I think my simpler depiction as seen in the one I most recently created generalizes and covers the entire process much better.

This provides self-reported evidence that the students believed their comprehension of the course material increased in quality, despite the lower number of terms and connections. These findings contradict previous research that suggests a correlation between the number of nodes and deeper knowledge of the subject (Borgatti & Everett, 1997; Walker & King, 2003). The mention of organization also can explain the decrease in interconnectivity and density within the concept maps, as the students seemed to break down the nodes of the concept maps into thematic sections that follow the product design process, thus creating fewer total connections.

5.3 | Changes in thematic elements

The thematic analysis revealed changes in the themes, subthemes, and interconnectivity present in the students' mental models of product design before and after the course. One interesting finding is about the influence of weekly course topics in Figure 7, showing that in almost every case, the change from precourse to postcourse prevalence of a theme moved in the same direction as the relative emphasis of the topic in the weekly course schedule. For example, in both courses, the proportion of *Engineering* topics in the weekly schedule was higher than the proportion of terms in the precourse concept maps, and this was reflected by a rise in *Engineering* term prevalence in the postcourse maps. More notably, the ME course placed a lower emphasis on *Business* topics, resulting in a decrease, while the EM/ISE course placed a nearly equal emphasis on *Business* topics, resulting in only a slight change. This confirms that the topics taught in these courses influenced the student' mental models of the subject matter.

While the EM/ISE sample did not have many statistically significant thematic changes, likely due to the smaller sample, the ME students showed substantial changes that aligned with the course topics. This included increases in ME students' percentages of terms in all subthemes of the *Engineering* category, decreases in all *Business* subthemes, and increases in most *Society* subthemes. Corresponding with the decrease in *Business* and *Interdisciplinary* terms was a decrease in cross-theme edges between these and other themes. Similarly, there was an increase in terms that connected *Engineering* and *Society*. This shows that in the ME course, students were exposed to the relationships between engineering and society in the context of product design, leading to a holistic understanding of these two dimensions of design.

Despite the small sample, the EM/ISE students did show some significant changes, mostly at the subtheme level. First, the *Technical skills* subtheme saw a decrease, which is expected as the students transitioned from general engineering courses to the broader topics of the Engineering Management and Industrial and Systems Engineering curricula, which emphasize project management and system-level problem-solving. The other significant subthematic change was in *Market* topics, which had the largest effect size of all changes. This shows the effectiveness of the market-driven design elements of the course, including the emphasis on user need elicitation, the use of market simulators, and the business planning content and assignments.

Regarding the *Interdisciplinary* terms, the overall decrease in frequency, shown in Figure 3, supports the argument discussed in Section 5.2 that the included terms became more specific and relevant to the course in the postcourse maps. *Interdisciplinary* terms are inherently broader than those categorized in the *Engineering*, *Business*, or *Society* themes. The decrease in *Interdisciplinary* terms may be attributed to improvements in the precision of language and specificity of terms over the duration of the semester.

5.4 | Recommendations for engineering design education

The results of this study provide insights to support curricular design, particularly for project-based design courses that seek to provide students with a more holistic perspective of product design. Figure 7 shows how the students appear to have learned what was being taught in the classes, where a prominent correlation emerged between the topics covered in the respective classes and the changes in the student perspectives on product design. For example, the ME curriculum places a much heavier focus on societal implications, whereas EM/ISE places more emphasis on business-focused topics such as market considerations, and there are corresponding changes in student perspectives indicating an effective connection between the teaching and learning practices applied in these classes. This indicates that educators who wish to instill particular topics or concepts in students' mental models may successfully do so by including weekly course modules on those topics, although it is likely that pedagogical techniques also played a role in the perceived effectiveness.

One challenge in analyzing the contents of large numbers of concept maps is the volume of unique terms, which requires a substantial amount of manual classification work. This can be addressed in the future by reducing all terms to their root words, as well as through the use of natural language processing technologies. Another challenge faced was the number of students available for the study, as convenience sampling was used with all students enrolled in these Design VI courses. Future studies may consider sampling from a wider range of engineering majors or choosing to include students from multiple universities. This would enable more significant findings and the ability to break down the data based on different factors such as student demographics or experiences.

5.5 | Theoretical contributions

Despite the limitations of the study (see Section 3.6), several theoretical implications are inferred from the results that advance our understanding of student learning and lay the foundations for future research. From the concept map analysis, specific themes and subthemes emerged from the data (see Sections 4.3 and 4.4). This categorization scheme was not predetermined; rather, it was developed through an iterative process by the research team, based entirely on the terms generated by the participants. This theme and subtheme structure may be used as a basis for future studies in product design learning, as well as for educators teaching product design. This may remove or reduce a substantial scoping burden for future researchers, which is a documented challenge in this type of study (Simpson et al., 2008).

Furthermore, the results from studying this cohort of students provide one set of data that may serve as a meaningful baseline for future research into design conceptions. In particular, the relative percentages of different themes and subthemes in the students' conceptual understandings, the comparison of those themes and percentages to the course objectives, and the changes in those percentages through these design courses may serve as a theoretical foundation or basis for comparison in future work. One notable takeaway about student conceptualization is a lack of societal term consideration, which shows an opportunity for more balanced design education in that domain. Consequently, this study highlights the need for the inclusion of discussions in engineering learning environments focused on the role of societal contexts in how we design or seek to provide solutions. Engineering instructors may also consider how they can assist their students in acknowledging the practical applications of theoretical concepts through their discussion of course content and completion of course activities and assessments.

From a methodological standpoint, this study has developed and tested a theoretically-grounded mixed-method approach to concept mapping research (Wheeldon, 2010). Previous studies have analyzed structural components such as the number of nodes and overall density, as well as content components, such as analyzing the presence of themes (Walker & King, 2003). Both of these approaches were applied in this study to provide a complete analysis of the concept maps, and additional data were collected and analyzed to provide more context to the otherwise strictly quantitative results. Analyzing data from reflections and connecting the map terminology to the course syllabi helped bring contextual insights to the findings, particularly when they conflicted with results from previous literature. The methodology developed and demonstrated in this article is recommended for future classroom-based concept mapping studies.

One notable concept map analysis finding is the disconnect between student learning and quantitative measures from the concept map structures (see Table 4). Some prior studies used an increased number of nodes, edges, and density in a concept map over time as a representation of increased knowledge and understanding (Borgatti & Everett, 1997; Novak & Gowin, 1984; Walker & King, 2003). However, this study did not see a consistent increase in structural elements, with only one of the structural metrics changing in a statistically significant hypothesized manner. However, other parts of the analysis showed evidence of increased learning, as discussed in Sections 5.2 and 5.3. This provides an argument against the use of structural analysis methods as a lone metric to measure learning through concept maps.

5.6 | Future research opportunities

For addressing the limitations described in Section 3.6, several new research directions are suggested to advance this understanding of student learning and the education-practice skills gap. First, one potential research path is to use this methodology for students across a broader sample of schools, programs, and backgrounds nationwide. This can provide a general baseline for how engineering students think about and understand product design when entering the workforce and which curricula are most effective in providing an appropriately holistic understanding of design, expanding on the known skills gap. The findings could support educators and curriculum designers to reprioritize their topical focuses to better prepare new graduates for their professional careers.

Second, another research opportunity is to assess the conceptual understandings of current successful engineers with experience in their respective engineering industries. While no expert map was used in this study, one could be created by having professional engineers generate concept maps, either as individuals or in groups. This could then be cross-referenced with internal performance data to theorize an ideal balance among the thematic and subthematic areas. By comparing this ideal ratio to recent engineering graduates and current engineering students, curricular gaps can be identified and addressed.

Third, this study showed that concept mapping in this fashion could be used as a self-assessment tool for the effectiveness of course curricula. In the case of this study, increased specificity in vocabulary, as well as the correlation between course topic themes and concept map thematic analyses, have demonstrated the effectiveness of these two Design VI courses in teaching the topics on the syllabi. This process can help professors adjust their curricula, receiving feedback from the maps to see how well their changes were retained by the students. This method could be applied to measure the effectiveness of other types of courses beyond the engineering field as well.

Finally, the concept mapping approach itself presents another avenue for further research. Understanding how to design, implement, and analyze concept maps more effectively can be useful to countless future research endeavors. For example, because this study was exploratory, our participants were tasked with creating maps based on broad sweeping terms, that is, product design. Other studies that employ concept maps for data collection may consider using more targeted language/concepts guided by their theoretical framework or previous literature. This might provide stronger boundary conditions for the concept maps, thereby producing maps that are more focused rather than broad.

Additionally, while the structural analysis of concept maps was inconclusive in this case, the thematic analysis presented interesting findings. Developing more precise measures of understanding to be included in future structural analysis or automated ways to digitize and analyze batches of concept maps requires additional research. Moreover, finding effective ways to combine qualitative analyses of the concept maps, as well as other assessment instruments, such as reflections, with the quantitative analyses included in this study could improve the methodological approach in future research.

6 | CONCLUSIONS

Engineering design is widely recognized as a critical component of engineering education that can help reduce the skills gap between education and industry. This study uses an exploratory, case-based approach to reveal how third-year undergraduates in two engineering programs conceptualize product design by collecting and analyzing concept maps both before and after a design course. The precourse analysis shows similar thematic distributions by students in different majors, with approximately 40% of terms in the *Engineering* category, 40% in *Business*, and 20% in *Society*. Comparing these findings to concept maps at the end of the courses found differences based on the degree program, with students taking the ME course increasing their concentrations of *Engineering* and *Society* terms and those taking the EM/ISE course increasing their concentrations of *Business* terms. These changes are aligned with the weekly course topics on the respective syllabi. In addition to this benchmark quantitative data on student conceptualizations, this article also puts forward a thematic categorization scheme for concept maps about product design, as well as a methodological approach to study student conceptual learning through concept maps. The findings from this study, as well as the future research opportunities discussed in Section 5.6, are geared toward helping engineering educators better understand student learning, quantify the skills gap, and improve engineering design curricula.

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