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Using Concept Maps as a Tool for Assessment and Continuous Improvement of a First-Year Course

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Utilizing concept maps as an assessment and continuous improvement tool for a redesigned first year course

Abstract

This paper demonstrates evidence-based practice for evaluating the effectiveness of and continuing to improve a first year course on engineering fundamentals and decision-making. In Spring 2015, five instructors in the Department of Engineering at James Madison University taught six sections of an introductory engineering course. The course is a curricular element of the department's first-year experience and is intended to introduce new engineering students to engineering fundamentals, analytical and creative problem solving, systems thinking, engineering and society, sustainable development, and professionalism. As part of course assessment, students completed hand-written concept maps of "engineering decision-making" during the first and last weeks of class. A concept map is a graphical method for identifying and organizing relationships between concepts, related to a central topic, by using a node-link diagram. The instructors wanted to discern if students broadened and deepened their understanding of engineering decision-making over the course of the semester and identify gaps or misconceptions that will need to be addressed during students' subsequent courses and by future runs of the first-year course. The pre and post concept maps were completed during class time in the first and last weeks of the semester. Students were given a brief explanation and examples of how to construct a concept map, using a common set of slides in each section, and then had 10 minutes to complete the maps. The pre and post concept maps were evaluated for structure and connectedness of knowledge using the traditional scoring method which counts and then weights the number of concepts, the number of hierarchies (or branches), the depth of hierarchies, and then number of cross-links connecting different hierarchies. The content of student knowledge was evaluated using thematic analysis to identify trends or gaps in student knowledge compared to the course learning objectives. The results, in terms of both structure and content of student knowledge, suggest that students' conceptualizations of engineering decision-making evolved over the course of the semester but that gaps (or low prioritization) between course learning objectives and student conceptualizations may exist. Course instructors are using the results of concept map analysis to continuously improve the course during the Spring 2016 and in future semesters. The instructors would like to help the students make stronger connections between course topics and how each can be incorporated into decision-making for both simple and complex problems. Concept maps are a method that can be employed by other institutions that are assessing a first-year course or have multiple instructors or multiple sections of a first-year course in order to help establish a consistent foundation for future classes. Concept maps are valuable as both a learning tool, helping students make connections within or across classes, and as an assessment tool to inform and monitor the effectiveness of curricular interventions to improve student learning.

Introduction

Engineering curricula have been shaped by five major shifts over the past one hundred years; the three "shifts" still shaping engineering education include a renewed emphasis on design; the use of research-based practices for curricula design and teaching methods; and the prevalence of computer-based communication and technologies in engineering education[1]. First-year engineering courses continue to evolve within the shifting landscape of engineering education.

The majority of ABET-accredited engineering programs prescribe or recommend a sequence of introductory courses that may include science, mathematics, general education, and introductory engineering requirements. In a review of over 1,800 ABET EAC-accredited programs with an introductory course sequence, Chen (2014) identified 1,651 engineering programs that offer a 2-term suggested introductory course sequence, representing 88% of the accredited programs with a first-year curriculum. Of those 1,651 programs, 16% require or recommend an engineering course in the first term and 17% require an engineering course in the second term. Considering all of the two-term institutions further, Chen determined that approximately 95% of engineering course credit in those programs is mandatory for students to complete. The engineering courses could be classified as "general engineering" or "disciplinary engineering" courses.[2]

Chen (2014) also analyzed course descriptions of 2,222 non-repeated first-year engineering courses to identify topical key words using a revised First-Year Engineering Course Classification Scheme[2,3]. On average, first-year engineering courses listed 5-6 different topics, with 8% listing only one topic and less than 1% listing twenty or more topics. The most frequently listed topics (not in rank order) included engineering profession, disciplines of engineering, engineering careers, and roles and responsibilities of engineers, problem solving skills, laboratory experiments, software tools, programming skills, Computer Aided Design (CAD), graphics, circuits, problem solving skills, basic design concepts, design project assignments, engineering analysis, formal design process, teamwork, engineering ethics, writing skills, data estimation, and academic advising. The least frequently listed topics (though still present) included stress management, academic integrity, interviewing, poster communication, brainstorming (design fundamental), social entrepreneurship, empirical math functions, client interactions, and qualitative research skills. These skills were only included in one or two courses each[2]. The range in both number and categories of course content reflects the variability in first year course experiences for engineering students.

A call was put forth several decades ago (i.e., the mid-1980's) to postsecondary education to focus on the first-year experience of college students[4] because the transition from high school to college is a pivotal point in the lives of most students and particularly critical for engineering programs which experience high attrition rates[5].While students continue to learn and expand their view of engineering over multiple years, the content of first-year courses could have long-term influence on what students' consider important to engineering and thus value in their education[2,6].

Case Study Context

The undergraduate engineering program at James Madison University (JMU) is ABET accredited through the Engineering Accreditation Commission. The program was designed to develop engineering graduates aligned with the vision of the Engineer of 2020 by the National Academy of Engineering: one who possesses strong analytical skills, strong communication skills, a strong sense of professionalism, creativity, and versatility[7]. The curriculum combines a liberal arts general education core with courses in math, science, engineering design, engineering science, engineering management, systems analysis, and sustainability to prepare engineering versatilists[8]. The department has experimented with multiple combinations and iterations of a first-year experience since 2008, including one or two required engineering courses along with math, science, and general education courses in the first two semesters. Several faculty are currently engaged in reimagining the first year experience as a two-course sequence that facilitates students' transition into college through engineering fundamentals and authentic, problem-based learning. This paper focuses on continuous improvement of the second course in the sequence. The introduction to engineering course has been offered since 2008 as a required three-credit course[9]. Previously offered in both fall and spring semesters, it is now offered only in the spring semester and meets twice per week for 100 minutes each session with approximately twenty-five students per section.

Introduction to Engineering Decisions Course

In Spring 2015, five instructors in the engineering department launched six sections of the revised introductory engineering course. The course is meant to prepare students with the knowledge, skills, and attitudes required to make informed engineering decisions while learning about the engineering profession and the requirements for successful progression through the Madison Engineering program.

The course outcomes, in terms of what first year students will be able to do, can be mapped to ABET EAC criteria and are as follows:

• Apply fundamental physical principles, mathematical relationships, dimensional analysis, and calculations to enhance engineering decision-making skills (ABET a)
• Accurately and appropriately use analytical and physical prototyping to evaluate trade-offs and make informed engineering decisions (ABET c)
• Apply a methodical approach to understand and analyze problems (ABET e)
• Communicate and justify decisions to a broad audience in a professional manner (ABET g)
• Learn independently using a variety of commonly available resources (ABET i)
• Use common engineering tools and software to solve engineering problems. (ABET k)

In order to achieve those objectives, each instructor addressed the following course topics through readings from a common textbook, homework exercises, and project application:

- Madison Engineering
- Succeeding in the Classroom
- Problem Solving
- Visualization and Graphics
- Computer Tools
- Engineering Ethics
- Units & Conversions
- Mathematics
- Engineering Fundamentals.

An interactive lecture format with application sessions was the predominant structure for each section, although teaching style and specific content varied at the instructor's discretion. Class sessions and student work focused on knowledge-building and/or skill-building and featured a range of problem types from simple and well-structured "book problems" to more complex and less defined problems with extraneous information or multiple assumptions. Through different types of problems, students learned and applied engineering fundamentals of statics, dynamics, circuits, thermodynamics and heat transfer, and economics along with other substantive threads prevalent in the Madison Engineering curriculum like systems thinking and sustainability.

Students were presented with additional skill-building topics that required out of class time and self-paced completion of the work. The skill-building or tools-based topics included exposure to MATLAB, Excel, and Solidworks. Students were encouraged to learn the basic skills (i.e., navigating the interface, using proper syntax, recreating a simple part, etc.) independently through guided tutorials (e.g. lynda.com modules). The out-of-class learning was complemented with in-class workshops during which students learned about and practiced more complex tasks like lifecycle assessment of materials or flow simulation in SolidWorks. Students also had the opportunity to complete hand and power tools training and learn about the capabilities of the engineering 3-D print lab so that they could build physical models. In addition, each section incorporated a semester-long team project designed to integrate and apply the knowledge and skills learned throughout the course, although project topic varied across sections with three different projects represented.

For each section, the semester culminated in a project presentation during the department wide end of the year showcase which brought together students, faculty, staff, parents, friends, external partners, and the interested public to share student projects and accomplishments from the 2014-15 academic year. During the event, first-year teams demonstrated their project solutions and had the opportunity to interact with their clients and other members of the Madison Engineering community. First-year students could also learn from their classmates in the other five sections to see how the different project teams applied the same fundamentals to solve very different problems. In addition, first year students explored course, capstone, and honors projects completed by upper level students. The event was an opportunity for first-year students to preview what is to come in their undergraduate engineering academic careers and also have a chance to ask questions and challenge the upper level students.

Methods and assessment using concept maps

As part of course assessment, approximately 120 students enrolled in the introductory course completed hand-written concept maps during the first and last weeks of class in response to the prompt "what is engineering decision-making". A concept map (as shown in Figure 1) is a graphical method for identifying and organizing relationships between concepts (e.g., ethics or safety), related to a central topic (e.g, engineering decision-making), by using a node-link diagram. They can be created by hand or using a variety of freely available computer programs. Concept maps enable the instructor to evaluate the structure and content of student knowledge. From a theoretical basis, concept maps are supported as learning and assessment tools by semantic memory theory from cognitive psychology research[10-12].

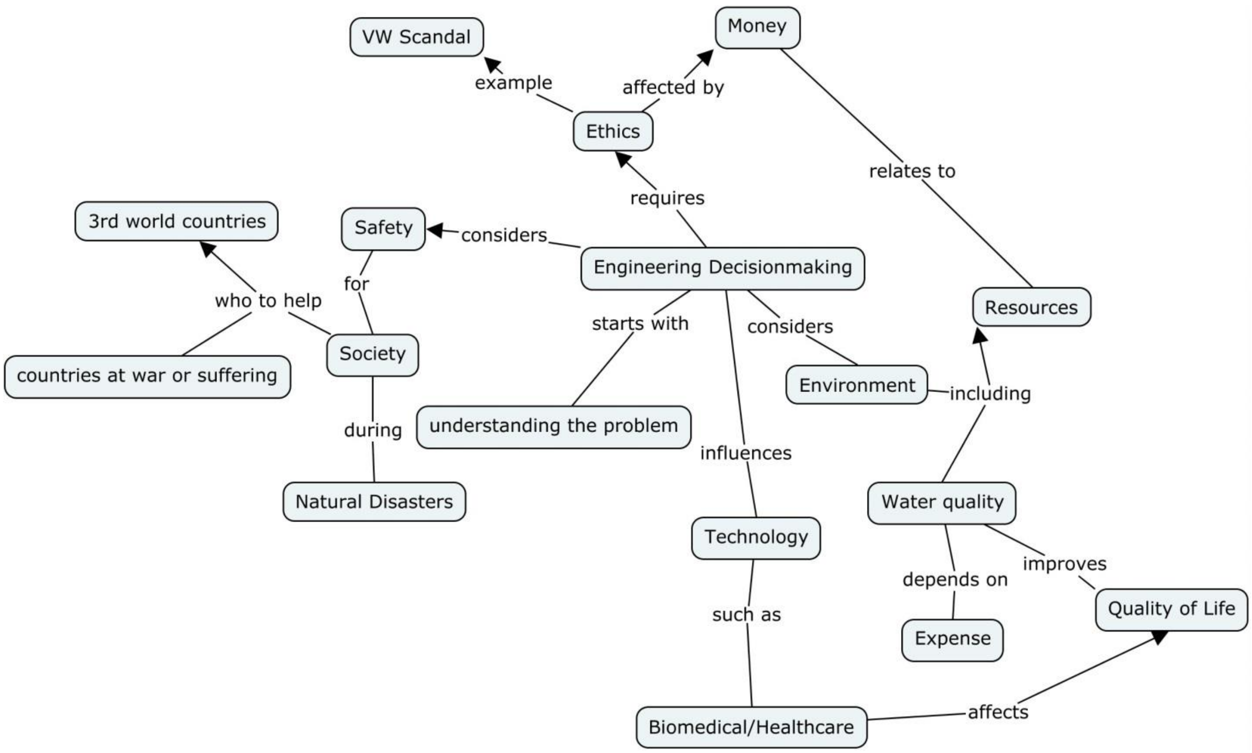

Figure 1. An example concept map of what is “engineering decision-making”? (Created using CmapTools, http://cmap.ihmc.us/)

The pre and post concept maps were completed during class time in the first and last weeks of the semester. Students were given a brief verbal and visual explanation and examples of how to construct a concept map, using a common set of slides in each section, and then had approximately ten minutes to complete the maps.

As an assessment tool in engineering education, concept maps can be scored in a number of ways[13,14] including the traditional method[15] which evaluates structure and connectedness of knowledge in terms of the number of concepts, the number of hierarchies (or branches), the depth of hierarchies, and the number of cross-links connecting different hierarchies. For example, Figure 1 would be scored as follows using the traditional method: number of concepts equals 16, number of hierarchies equals five (branching off of “engineering decisionmaking”), highest (or deepest) hierarchy equals three and number of cross-links equals two.

One scorer was utilized to evaluate all concept maps at the end of the course; the scorer completed training and calibration sessions with an experienced concept map scorer so that there was consistency across the pre and post scoring. In addition to evaluating the structure of student knowledge, the content of the concept maps was evaluated using thematic analysis to identify trends or gaps in student knowledge compared to the course learning objectives and to ascertain shifts from the beginning to end of the course.

Analysis of pre and post concept maps

Student concept maps from four sections of the introductory course (representing four different instructors and three different term projects) are included in the results and analysis. All completed pre and post concept maps were evaluated quantitatively and qualitatively.

Traditional method scores

Quantitative measures of students' pre and post concept maps are provided by scores from the traditional method.

Table 1 shows the average and standard deviation of the pre and post scores for each of the measures (i.e. number of concepts, crosslinks, hierarchies, and highest hierarchy) aggregated across all classes. As the table shows, there was an increase in average scores across all measures. In addition, the standard deviations increased, suggesting a greater range of performances across students.

Table 1. Average and St. Dev broken down by Pre-Post for each measure.

Statistic	Pre	Post	Change
Avg. No. Concepts	21.07	29.77	8.70
Avg. No. Crosslinks	1.35	2.48	1.13
Avg. No. Hierarchies	5.60	7.35	1.75
Avg. Highest Hierarchy	3.02	3.65	0.63
Std. dev. of No. Concepts	8.46	11.86	3.40
Std. dev. of No. Crosslinks	1.88	2.44	0.56
Std. dev. of No. Hierarchies	2.25	3.70	1.45
Std. dev. of Highest Hierarchy	1.07	1.59	0.52
Number of Records	81	65	

Figure 42 shows the difference in the pre-post scores broken down by each of the four sections. With the exception of one measure in Class A (i.e. number of hierarchies), there was an increase across the average measures between the pre and post maps.

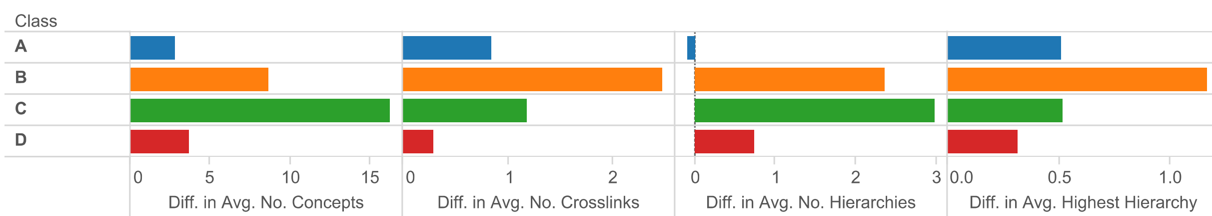

Figure 2. Difference in pre and post averages for each measure broken down by Class. Color shows details about Class.

Additionally, paired two-sample t-tests were performed to determine if concept map scores increased from pre to post. Any unpaired student concept maps were removed, resulting in 61 pre and post concept maps considered in this analysis. Unpaired concept maps resulted from students dropping the course during the semester or being absent from class on either the pre- or post-test day. For the Number of Concepts, the mean increase from Pre to Post score (M=8.39, SD=9.98, N=61) was significantly greater than zero, paired t(60)=6.6, two-tail p=0.000. For the Number of Hierarchies, the mean increase from Pre to Post score (M=1.54, SD=3.05, N=61) was also significantly greater than zero, paired t(60)=3.9, two-tail p=0.000. For the Highest Hierarchy, although the mean increase from Pre to Post score was modest (M=0.66, SD=1.65, N=61), the increase was significantly greater than zero, paired t(60)=3.1, two-tail p=0.003. Finally, for the Number of Crosslinks, the mean increase from Pre to Post score (M=1.18, SD=2.77, N=61) was significantly greater than zero, paired t(60)=3.3, two-tail p=0.001. Although the increases were modest for some parameters, such as depth of hierarchy and number of crosslinks, all measures demonstrate a statistically significant improvement from pre to post scores. In addition to recognizing a greater breadth of factors in engineering decision-making as indicated by number of concepts, students also captured greater complexity of engineering decisions as indicated by the other three measures.

Content Analysis

While the traditional method provides quantitative scores of students' knowledge and connection building, the content of students' concept maps can help provide a more complete understanding of how they viewed engineering decision-making at the beginning and end of the course and what they learned (or did not learn). Figures 3 and 4 are visual depictions of which concepts or terms were most frequently included in students' pre and post concept maps – the larger the word, the more often it was used. The word clouds shown below provide a quick way to ascertain which themes were most prominent across all student maps.

Figure 3. Aggregated content from Pre concept maps (created with Wordle™)

Figure 4. Aggregated content from Post concept maps (created with Wordle^{TM})

Taking a closer look at the content of the concept maps, Table 2 is derived from the word counts provided by the Wordle^{TM} program. For discussion and presentation purposes, the content analysis was limited to approximately the top 50 terms, which were used by 10 percent or more of the student respondents. Based on the ranking of the terms, Ethics and Cost were consistently the top concepts listed by students, and there are many similarities in content across the two lists although the prevalence of certain terms (either up or down) changed significantly in some cases. For example, prototype/prototyping, which was an emphasis of the courses was in the top ten most frequently used terms in the post concept maps (used by 37% of students) but not even in the top 25 in the pre concept maps. Several terms (safety, design, ideate, prototype, economics) made significant jumps in the rankings from pre to post concept maps while others dropped noticeably (laws/legal, moral/morally, public, product) or were seemingly replaced by new or more specific language (e.g., "client" replaced "people").

Table 2. Top terms used in student concept maps to describe "engineering decision-making"

PRE (n=81)				POST (n=65)		
Word	Freq.	% students		Word	Freq.	% students
Ethical/ethics	53	65%		Ethical/ethics	56	86%
Cost/costs	33	41%		Cost/costs	36	55%
Environment/environmental/environmentally	23	28%		Sustainability/Sustainable	36	55%
Problem/problems	21	26%		Safe/safety	33	51%
Sustainability/sustainable	21	26%		Environment/environmental/environmentally	32	49%
People/people's	20	25%		Client/clients	29	45%
Time	20	25%		Design/designs/designed/designing	28	43%
monetary/money	19	23%		Economic/economical/economically/ economics/economy	26	40%
Social/socially/societal/society	19	23%		Prototype/Prototypes/Prototyping	24	37%
Design/designs	18	22%		Idea/ideas/ideate	22	34%
Safety/safe	18	22%		Problem/problems	21	32%
Engineer/engineers/engineering	15	19%		Time	19	29%
moral/morally/morals	15	19%		brainstorm/brainstorming	17	26%
Work	15	19%		Human-centered	17	26%
Group/groups	14	17%		Materials	17	26%
Law/laws/law-abiding/legal	14	17%		Social/socially/society	17	26%
Project/projects	14	17%		Code	16	25%
Brainstorm/brainstorming	13	16%		Research/researching	16	25%
Public/public's	13	16%		Analysis/analyze/analyzing	14	22%
Ideas	12	15%		Engineer/engineers/engineering	14	22%
Material/materials	12	15%		Resources	14	22%
Solution/solutions	12	15%		Money	13	20%
Benefit/benefits	11	14%		Needs	13	20%
Efficiency/efficient	11	14%		Tools	13	20%
Impact/impacts	11	14%		Dynamics	12	18%

Process/processes	11	14%		know/knowledge	12	18%
Profit/profits	11	14%		Profit/profitable/profits	12	18%
Research/researching	11	14%		Efficiency/efficient/efficiently	11	17%
Effective/effectiveness	10	12%		Help/helpful/helpfulness/helping	11	17%
Help/helped/helpful/helping	10	12%		How	11	17%
prototype/prototypes/prototyping	10	12%		Process	11	17%
Resources/resource	10	12%		Solidworks	11	17%
Right	10	12%		Solution/solutions	11	17%
Better	9	11%		Solve/solving	11	17%
Economic/economical/economically/ economics/economy	9	11%		Technical/Technological/Technology/tech	11	17%
Manage/management	9	11%		Benefit/benefits	10	15%
New	9	11%		Creative/creativity	10	15%
Solve/solves/solving	9	11%		Discover/discovery	10	15%
Team/teams/teamwork	9	11%		Impact/impacts	10	15%
What	9	11%		Math	10	15%
Good	8	10%		model/models/modeling	10	15%
Mechanical	8	10%		Who	10	15%
Need/needs/needed	8	10%		CAD	9	14%
Outcome/outcomes	8	10%		Calculations	9	14%
Plan/planning/planned/plans	8	10%		moral/morals	9	14%
Product/products	8	10%		outcome/outcomes	9	14%
Quality	8	10%		Static/statics	9	14%
Technological/technology/technologies	8	10%		Better	8	12%
Think/thinking	8	10%		Circuits	8	12%
Usage/use/uses/used	8	10%		Empathy	8	12%
Who/whom	8	10%		Feasibility/feasible	8	12%
				People	8	12%
				Physics	8	12%
				System/systems/subsystems	8	12%

Discussion

Concept maps are valuable as both a learning tool, helping students make connections within or across classes, and as an assessment tool to inform and monitor the effectiveness of curricular interventions to improve student learning. Quantitative scores suggest how the complexity and structure of student knowledge or values with respect to engineering decision-making changed over the course of the semester. Based on the results of this review, students may have a more complete and complex view of how engineers make decisions and used new concepts learned during the course to describe decision-making. Some of the learning objectives, like engineering fundamentals (e.g., units, statics, dynamics, circuits, economics, etc.) and prototyping, became much more prominent and represented in more detail (e.g., listing "statics" versus simply "analysis") in the end of semester cmaps. Students also cited key phases of the design process (e.g., discovery, empathy, ideate/brainstorm, prototype, analysis), which was a common objective across sections and relates to an ABET learning outcome. Further, the post concept maps reflect both analytical and physical approaches to design and problem-solving and use more technical, specific language. Another area in which students' language became more specific was in referencing specific software programs (most notably, SolidWorks) as key to decision-making to a greater extent at the end of the course. This likely reflects the various training modules that students completed throughout the semester and the visual component of their term projects, for which many teams used a CAD program (i.e. SolidWorks).

As another example of a shift, the post-maps show a more obvious orientation towards designing and solving problems for other people as indicated by the higher use of terms like "client", "human-centered", and "society". Client did not even appear in the top 50 in the pre-concept maps. While this was not an explicit learning objective, a client/stakeholder orientation is emphasized throughout the engineering curriculum and could also indicate greater student motivation for the ABET student outcome g (communicating and justifying decisions to a broad audience). Interestingly, communication-related terms were not prominent features of either pre or post concept maps although "group" and "team" were cited. Students may not fully grasp the importance of clear, technical communication of their ideas and decisions. Communications may represent a potential area for improvement if other course evaluations (memos, presentations, drawings, etc.) reveal a similar gap in student learning or valuation of the importance.

There seemed to be a general convergence in the most frequently cited concepts as indicated by higher percentages of students using the same terms that appear in the top 50, often independent of whether rank went up or down. For example, "social/socially/society" is ranked higher up the list on the pre-maps than the post-maps but was cited more frequently on the post-maps (26% vs 23%).

In terms of continuous improvement, the content of the students' concept maps suggest a few surprising gaps or shifts. For example, "systems" is an important curriculum theme throughout the engineering program but was not highly used by students in describing engineering decision-making. As another example, students' maps placed a more significant emphasis on the physical/hands-on aspects of design (e.g. generating and prototyping concepts or the use of "tools") rather than the analytical modeling or evaluation aspects of design. The "tools" emphasis likely reflects the hand and power tools training that all students receive along with the use of CAD and analysis software. This emphasis is perhaps unsurprising as first year students have limited exposure to engineering training. However it may represent an area for improvement in order to help students develop a more balanced view of methods used in engineering decision-making, and prepare them to develop both physical and analytical methods as they progress through the curriculum. As a new iterations of the course is run, instructors are more aware of the impact of language and emphasis of certain content areas that students either gravitated towards. The instructors would also like to maintain the focus on human-centered design, specifically for outside clients, and the application of engineering fundamentals to design problems. This greater awareness and proactive changes in instruction can help provide students with a firmer and more consistent foundation in the core values of the department and important dimensions of engineering decision-making.

Conclusions

The results, in terms of both structure and content of student knowledge, indicate that students' conceptualizations of engineering decision-making evolved over the course of the semester but that gaps (or low prioritization) between course learning objectives and student conceptualizations may exist. Course instructors are using the results of concept map analysis to continuously improve the course during the Spring 2016 and in future semesters. The instructors would like to help the students make stronger connections between course topics and how each can be incorporated into decision-making for both simple and complex problems. Concept maps are a method that can be employed by other institutions that are assessing a first-year course or have multiple instructors or multiple sections of a first-year course in order to help establish a consistent foundation for future classes. The analysis presented in this paper can be utilized by other engineering programs in their assessment efforts for first-year courses and programs. Concept map administration, scoring, and analysis can be completed without specialized analysis software. Thus, concept maps are valuable as both a learning tool, helping students make connections within or across classes, and as an assessment tool to inform and monitor the effectiveness of curricular interventions to improve student learning.

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