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Evaluating a new second-year introduction to chemical engineering design course using concept mapping

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Abstract

In recent years engineering curricula have had a renewed focus on engineering design. At the University of British Columbia undergraduate students have a general first year and then apply to engineering majors for their second-year of study. In the first-year engineering program, there is a two-course sequence where students are introduced to general engineering design. This is done through a variety of case studies in modules lasting 3 to 4 weeks.

The Chemical and Biological Engineering Department through consultations with stakeholders such as students, faculty, alumni and industry saw a need to integrate more engineering design practice into the second and third years of the undergraduate programs it offers. Based on this, the department has introduced a series of two new second-year undergraduate courses introducing engineering science fundamentals and design. These courses integrate some content from courses they replace while also introducing new content, specifically around engineering design. The new second-year courses build on student design experiences from first-year while introducing students to more discipline-specific design processes. The first course in this series focuses on chemical engineering and the second course on biological engineering. This current research focuses on the impact of the first course in this series.

Concept maps have been shown to be a powerful and flexible way of assessing student learning. They have been implemented in a wide variety of contexts such as in design and conceptual knowledge assessment. Students were asked to create a concept map for chemical engineering at the start (pre) and end (post) of the course outlining the 10-20 most important concepts in chemical and biological engineering and how they are related. Students completed this exercise using a concept mapping tool (CmapTools). These responses were then analyzed using a thematic analysis. Results from this were used to compare common themes in class responses at the start and end of the course. It was found that students at the end of the course converged on five particular topics which were focus areas in the newly implemented design course, suggesting an effective teaching practice. A shift in themes was seen from scientific topics (eg. organic chemistry, math) to engineering science or design topics (material balances, energy balances, process control, etc), which can be explained by the gain in familiarity with the field.

Introduction

This paper will first describe the curricular context which led to the creation of a second-year introduction to chemical engineering design course. Then it will describe a technique used to evaluate concepts students deem most important in chemical and biological engineering using concept mapping and present results from this technique.

In recent years engineering curricula have had a renewed focus on engineering design [1]. There are a variety of definition of engineering design and the authors prescribe to the Engineers Canada definition outlined by the Engineers Canada graduate attributes. That is: "An ability to design solutions for complex, open-ended engineering problems and to design systems, components or processes that meet specified needs with appropriate attention to health and safety risks, applicable standards, and economic, environmental, cultural and societal considerations" [2]. This definition has many similarities to the ABET definition [3]. Examples of the renewed focus on engineering design can be found in many programs. These include the Engineering Design and Practice Sequence at Queen's University aiming to create a four-year design sequence across all engineering programs [4]. Another example is the project-based spiral curriculum implemented at Worcester Polytechnic Institute [5]. At the University of British Columbia undergraduate students have a general first-year program and then apply to engineering majors for their second-year of study. In the first-year engineering program, there is a two-course sequence where students are introduced to general engineering design (also known as "cornerstone" design courses). Students are introduced to design through a variety of case studies in 3 to 4 week-long modules within this first-year course sequence [6].

Following their first year, students would then enter the department of Chemical and Biological engineering. The next major design course for students in the department was their capstone course in the final year of their studies. Consultations with students, faculty, alumni and industry stakeholders indicated a need to integrate more engineering design practice into the second and third years of the undergraduate programs in order to better prepare students for their careers. In response to these concerns the department undertook a major review of its second-year curriculum. The most significant change was the introduction of a series of two new second-year undergraduate courses. These courses integrate some content from courses they replace while also introducing new content, specifically around engineering design. The new second-year courses build on general engineering design experiences from first-year while introducing students to more discipline-specific design processes, namely those associated with process design [7]. The first course in this series focuses on chemical engineering and the second course on biological engineering. This current research focuses on the impact of the first course in this series, Chemical and Biological Engineering (CHBE 220), and how it affected students' perceptions of the field of chemical and biological engineering. CHBE 220, and the courses it replaced, as well as the major topics of focus of these courses are outlined in Table 1.

Table 1: Courses existing before and after curriculum changes including major topics covered

Before curriculum changes	**After curriculum changes**
CHBE 243: Introduction to Chemical and Biological Engineering Process and Technology (1 credit) Major topics: • Introduction to a variety of relevant chemical and biological engineering industries through guest speakers	CHBE 220: Foundations of Chemical and Biological Engineering I (4 credits) Major topics: • Process design project definition • Block flow diagrams (BFDs) • Reaction kinetics

<table>
<tr>
<td>• Process design exercises done in teams in class focusing on process synthesis</td>
<td rowspan="2">• Physical properties relevant for separations
• Energy balances
• Process flow diagrams (PFDs) and process and instrumentation diagrams (P&IDs)
• Process control
• Process economics
• Environmental assessment
• Process safety</td>
</tr>
<tr>
<td>CHEM 251: Physical Chemistry for Engineers (3 credits)
Major topics:
• Ideal and real gases
• Introduction to 0^{th}, 1^{st}, 2^{nd}, 3^{rd} law of thermodynamics
• Thermochemistry and standard enthalpies
• Reaction kinetics
• Ideal solutions and Raoult’s law
• Miscibility and phase diagrams
• Colligative properties</td>
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</table>

Concept maps are arrangements of concepts (or nodes) where lines (or links) may be used, with linking phrases if desired, to show relationships between concepts. Concept maps were devised in the 1970s by Novak and have been used to map what the learner knows about a subject [8]. Concept maps have been used in a wide variety of settings to assess different types of knowledge. An example of this in an engineering context is work by Sims-knight et al. for the assessment of design process knowledge using concept maps [9]. Concept mapping has also been used by Walker and King to explore student assessment and instruction in bioengineering [10]. Walker and King describe two studies they developed, the first of which they describe as criterion referenced (meaning a comparison of novice vs. expert) and focused on undergraduate students, doctoral students and faculty identifying and relating the 10-20 most important topics in their discipline. Walker and King found it difficult to compare novice and expert maps using quantitatively focused measures (such as line-node analysis or map structure) due to the variability within both novice and expert maps. This variability within a particular group was present again in a later study [11]. These findings are aligned with a large body of literature on quantitatively focused concept map scoring and the challenges associated with this [12], [13]. Walker and King then built on their first study with a second study, which they describe as norm-referenced (meaning a comparison amongst a group). This norm-referenced study evaluated longitudinal changes in student concept maps in a yearlong senior-level design class. The authors found that this was of considerable value in identifying growth in students’ conceptual understanding over time. In this study we have focused on using concept maps in a similar norm-referenced form to assess changes in student perceptions around important topics in their engineering discipline. We have based this on the work of Walker and King and adapted the question prompt they used in their first study with this being “What are the 10-20 most important topics in [your discipline] and how these are related?”.

Methodology

At the first week of the term, in the first tutorial session of the class, students enrolled in the course CHBE 220 were presented with an exercise to use concept mapping to outline the 10-20 most important concepts in chemical and biological engineering and map out how these concepts were related. Students in the class were first presented with a consent form approved by the university's Research Ethics Board explaining the study. All students in the course were asked to complete concept maps and these were marked only for completion. Concept map data from students not opting in to the study was not used for further analysis. Students were then presented with a brief document explaining how to install Cmap Tools software, which is a free software for concept mapping [14]. This software was also made available on computer lab computers if students did not have or want to install the software on their own computers. Students were then presented with a 1-page document explaining how to create concept maps using Cmap Tools. No sample concept maps were provided so as to not bias how students use the software or construct their maps. The document also explained how to use a built-in recording tool when creating their concept map. Finally, the document had a prompt for students, which was: "What are the 10-20 most important concepts in Chemical and Biological Engineering and how are they related?". Students were given 2 hours to access the software and complete this exercise and another concept mapping exercise afterwards. Once the software was installed and students were familiar with it, most students completed this exercise in 20 minutes or less. Students who did not complete the exercise in class had the option to submit it within 24 hours of the tutorial period. The same exercise was done at the end of the term using identical instructions, with some minor technical changes in instructions to ensure recording answers went more smoothly. This end of term concept mapping was completed during a 1.5 hour class session in the last week of class and students were again allowed to complete the assignment within 24 hours of the in-class session. The documents used in this study including consent form and instructions can be accessed on "https://github.com/OpenChemE/Concept-Maps".

Out of the class of 114 students, 82 consented for their data to be used. Out of these 82 consenting students, 56 students submitted files that could be analyzed at the start and end of the term. The 26 that could not be analyzed included 10 students who submitted the same file at the start and end of the term, while the other 16 students were missing a file for analysis (either at the start or end of term).

As previously discussed, the focus of this research is to assess change in students' view of key concepts in chemical and biological engineering over time. The study thus focuses on norm-referenced as opposed to criterion-referenced analysis. A range of analysis tools were explored to see which methods might give insight into the data collected. Contents of concept maps have been divided into three general categories for analysis with these being size, quality and structure [15]. Size and structure concept map analysis methods such as line and node counting [10] or centrality of concepts [15] were considered, but not selected due to previous literature indicating these methods may not provide insightful results when performing analysis on student concept map data generated from prompts such as the one used in this study [10], [12], [13]. Quality analysis is generally carried out by evaluation of a concept map by expert rating and can be done qualitatively or quantitatively [15]. Thematic analysis [16], which has been used in a wide variety of contexts to analyze themes in a piece of work was found to be a good fit for this study in qualitatively analyzing key concepts that students presented in their concept maps. The framework outlined by Braun and Clark was used to guide our choices in using thematic analysis and in attempting to make these choices clear [17].

Results and Discussion

The concept maps of the 56 students were analyzed for content by grouping concepts into themes. Theme identification was performed using the following process. The authors began theme analysis expecting themes which included common first and second-year course topics, engineering topics in CHBE 220 and common industrial areas. A list of these initial themes developed before looking at responses can be found as bolded text in Table 2. Thematic analyses were conducted independently by both authors on 10 concept maps from the start of term and 10 concept maps from the end of term. Following this the authors met again and discussed themes identified outside of the ones initially developed, these themes are shown in Table 2 as underlined text. The authors then continued analyzing all remaining responses independently. Following this, the authors met again and assessed new themes, and these are shown as italic text in Table 2. Note that the themes identified by authors include key words that may be separated as another theme depending on how data is analyzed. Throughout the theme identification process these keywords were added to themes. Example of this are “profit” and “cost” being lumped under “economics” and the merger of “clean energy” and “renewable energy” into one theme. Grouping keywords into themes was discussed in the meeting after the initial analysis to ensure consistency. We do not attempt to list any such keywords subsets as this list would be very large. During coding a total of 94 themes were identified. Table 3 outlines the 15 most common themes emerging from concept maps at the start and end of the course along with their frequency. A theme was only counted once for each student, even if they had multiple keywords mentioning that theme. A total of 538 concepts were counted for the maps at the start of the term, and 613 concepts at the end of the term. Following analysis, it was noted that most concepts identified fell within three general categories: disciplinary topics (eg. math, process control, etc.), industrial (eg. oil and gas, clean energy, etc.) and skills (eg. teamwork, critical thinking, etc.). We have grouped themes according to the category we feel they best fall into in Table 2 along with an “other” category for themes we felt did not fall into these categories. Following thematic analysis inter-rater reliability was calculated to be 0.707 using Cohen’s kappa [18]. This inter-rater reliability value falls into the category of very good (kappa = 0.60 to 0.79) using Regier *et al.*’s interpretation [19]. The data presented is results from the analysis of one of the authors.

Table 2: The 94 themes identified by authors. Initial themes expected before viewing concept maps are in **bold**, themes added after reviewing the first 10 concept maps are underlined, and themes identified analyzing the rest of the concept maps are *italicized*. The themes are organized into three general categories identified after coding and an "other" category.

Disciplinary topics	**Industrial**	**Skills**	**Others**
science	**oil & gas**	teamwork	waste
math	**clean/**renewable **energy**	critical thinking	product
physics	**energy (general)**	*collaboration*	materials/raw material
chemistry (general)	**water/wastewater**	*process thinking*	optimization
physical chemistry	**pulp & paper**	*presenting*	efficiency
organic chemistry	**mining/**metallurgy	*creativity*	stakeholders
inorganic chemistry	**materials engineering**	*professionalism*	computers
biological/biology	**pharmaceuticals/**medicine	*brainstorming*	upscaling
fluid mechanics/statics	**healthcare**	*analysis*	policy compliance/laws
laboratory	petroleum products		*technology*
computers/programming	manufacturing plants/factories		*Interaction with other disciplines*
thermodynamics	energy production		*prototyping*
communications	recycling		*yield*
diagrams	agriculture		*byproducts*
safety	*nuclear energy*		
economics	*product/factory lifecycle*		
environment/sustainability	*fuel*		
social considerations	*carbon capture*		
energy balance	*biofuel*		
material balance	*cosmetics*		
process Design	*fertilizers*		
process Control	*consumers*		
project planning/management	*energy usage/conversion*		
heat transfer	*nuclear weapons*		
material science	*quality control*		
reaction rate law/kinetics	*transportation/storage*		
social considerations	*plastics/polymers*		
equilibrium	*semiconductor*		
separation techniques	*career*		
research/innovation			
reactor design/reactors			
processes			
chemical reactions			
catalysis			
biotechnology			
ethics			
biomechanics			
electrochemistry			
nanotechnology			
bioprocessing			
unit operations			
Mass transfer			

Table 3: Top 15 themes at the start and end of the term, and number of students including the theme in their concept map.

	Start		End	
	Theme	**Frequency**	**Theme**	**Frequency**
1	Environment/Sustainability	34	Economics	47
2	Organic Chemistry	24	Environment/Sustainability	45
3	Inorganic Chemistry	22	Safety	41
4	Process design	21	Energy balance	40
5	Materials/Raw materials	19	Material balance	38
6	Upscaling	16	Process design	24
7	Safety	15	Process Control	21
8	Economics	14	Communication	19
9	Math	14	Reaction rate law/kinetics	16
10	Biological /Biology	14	Inorganic Chemistry	15
11	Thermodynamics	14	Organic Chemistry	15
12	Communication	13	Diagrams	15
13	Social Considerations	13	Thermodynamics	12
14	Waste	13	Social Considerations	12
15	Chemistry (general)	12	Equilibrium	12

The increase in overall concepts between start (538) and end (613) suggests students have gained more familiarity with the field. Although a frequency increase is expected at the end due to a higher number of concepts (14% increase), a 52% increase in frequency of the top 15 concepts shows student convergence in certain main themes describing chemical and biological engineering. The themes “economics”, “safety”, “energy balance” and “material balance” were significantly more present in the end of term concept maps. This change is expected since these are major course topics that are discussed not only in CHBE 220, but also in other courses that students take in the first semester of second year. Similar examples are the themes “energy balance” and “material balances”, which were mentioned 5 times at the start of the term but over 38 times at the end of the term. It is important to note that a core class in the CHBE curriculum is called “Material and Energy Balances”, and is likely a strong contributor to this difference.

The theme “diagrams” also had a significant increase in frequency from the start to the end of term from 0 to 15. This theme would be expected to increase since it is the first term that students start interpreting and creating chemical engineering diagrams such as block flow diagrams and process flow diagrams. Some other themes that had similar trends of high increase between start and end are “equilibrium” (1 to 12), “process control” (2 to 21), “reaction rate law/kinetics” (3 to 16), and “separation techniques” (0 to 11). All of these topics are heavily discussed in the first term of the second-year curriculum.

One can also note that subjects CHBE builds upon such as “chemistry”, “math” and “biology” were top themes at the start of the term but less prevalent at the end of the term. One explanation for this is that students are initially only exposed to the first-year curriculum, which is heavily based on the scientific foundations of engineering. As second year progresses, students focus less on natural science topics and increasingly focus on engineering science topics, perhaps helping to explain the change in top concepts.

Some themes have similar counts at the beginning and end of the term. Examples include social considerations (13 to 12), thermodynamics (14 to 12), ethics (3 to 2), water/wastewater treatment (5 to 7), optimization (7 to 8), alternative/clean energy (9 to 11). There are several possible explanations for this. These themes were not mentioned by many students at the beginning, and therefore, variations in students who mention them may not cause a noticeable difference in total count. These themes may also not be highly emphasized in first term second-year courses.

The top 5 most frequent themes at the end of the term had a significantly higher counts compared to the other themes at the end of term, while this distinction is not as clear in the start of term counts. The 5th most frequent theme at the start of the term was mentioned by 7 more students than the 15th most frequent theme at the end of term. Comparing the 5th most frequent at the end of the term to 15th most frequent at the star of term the frequency difference is 26. This suggests that students have somewhat converged into common definitions of items that represent chemical and biological engineering. A possible reason for this is that at the start of the term, students had never taken a course specifically focusing on chemical and biological engineering and may have had very different ideas of what the field entailed. On the other hand, at the end of the term students had spent 3 months taking the same classes and gaining familiarity with the field, and therefore, began to converge around certain key topics in describing chemical and biological engineering.

The study was undertaken with students writing their responses in relative isolation from one another. Students were asked to complete the activity individually although some students were discussing during the session and the instructional team did not intervene to limit this. It has been shown that having students reflect on their past work can be beneficial for learning [11], and a visual representation such as concept maps can be easily used for this. Departments can use concept maps to assess what students are drawing from the curriculum, as well as discovering areas that are considered essential but perhaps are not front of mind for students, thereby exposing areas for potential improvement.

Options for further study could include expanding the study to the end of the second term or future years. This may offer additional insight into how students' perception of chemical and biological engineering shifts over time. The study could also be adapted for a greater focus on social constructivism by encouraging students to discuss their concept maps with their peers and update them following this discussion [10]. Asking students to highlight the top 3 most important themes within their concept map could also give further insight into their idea of chemical and biological engineering.

Conclusion

Significant increases in themes that apply to engineering science and design such as economics, safety, material and energy balances, process design and process control suggest that the curriculum shifts students' perception towards discipline specific engineering topics. This is further supported by the decrease in frequency of foundational science themes such as math, chemistry and biology. A convergence around themes is shown by the higher frequency of common themes at the end of the term. This exercise can be implemented to expose mismatches between curriculum goals and student perception of a field, as well as a reflection exercise for students.

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References

[1] C. L. Dym, A. M. Agogino, O. Eris, D. D. Frey, and L. J. Leifer, "Engineering Design Thinking, Teaching, and Learning," *J. Eng. Educ.*, vol. 94, no. 1, pp. 103–120, Jan. 2005, doi: 10.1002/j.2168-9830.2005.tb00832.x.

[2] "Graduate Attributes," *Engineers Canada*. https://engineerscanada.ca/sites/default/files/Graduate-Attributes.pdf (accessed Mar. 10, 2020).

[3] "Criteria for Accrediting Engineering Programs, 2019 – 2020 | ABET." https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2019-2020/ (accessed Mar. 10, 2020).

[4] B. Frank, D. Strong, and R. Sellens, "The professional spine: Creation of a four-year engineering design and practice sequence," *Proc. Can. Eng. Educ. Assoc.*, 2011.

[5] W. Clark, D. DiBiasio, and A. Dixon, "A project-based, spiral curriculum for introductory courses in ChE: Part 1. curriculum design," *Chem. Eng. Educ.*, vol. 34, no. 3, pp. 222–233, 2000.

[6] P. M. Ostafichuk, C. P. Jaeger, J. Nakane, S. Nesbit, N. Ellis, and J. Sibley, "Redesigning the UBC first year introduction to engineering: successes and challenges," *Proc. Can. Eng. Educ. Assoc. CEEA*, 2016, doi: 10.24908/pceea.v0i0.6523.

[7] W. D. Seider, D. R. Lewin, J. D. Seader, S. Widago, R. Gani, and K. M. Ng, *Product & Process Design Principles: Synthesis, Analysis and Evaluation*, Fourth Edition. John Wiley & Sons, 2017.

[8] J. D. Novak, "Concept mapping: A useful tool for science education," *J. Res. Sci. Teach.*, vol. 27, no. 10, pp. 937–949, 1990, doi: 10.1002/tea.3660271003.

[9] J. E. Sims-Knight *et al.*, "Using concept maps to assess design process knowledge," in *34th Annual Frontiers in Education.*, Savannah, GA, USA, 2004, pp. 584–588, doi: 10.1109/FIE.2004.1408584.

[10] J. M. T. Walker and P. H. King, "Concept Mapping as a Form of Student Assessment and Instruction in the Domain of Bioengineering," *J. Eng. Educ.*, vol. 92, no. 2, pp. 167–178, Apr. 2003, doi: 10.1002/j.2168-9830.2003.tb00755.x.

[11] J. M. T. Walker, D. S. Cordray, P. H. King, and R. C. Fries, "Expert and Student Conceptions of the Design Process: Developmental Differences with Implications for Educators," *Int. J. Eng. Educ.*, vol. 12, no. 3, pp. 467–479, 2005.
[12] M. K. Watson, J. Pelkey, C. R. Noyes, and M. O. Rodgers, "Assessing Conceptual Knowledge Using Three Concept Map Scoring Methods: Assessing Conceptual Knowledge Using Concept Map Scoring," *J. Eng. Educ.*, vol. 105, no. 1, pp. 118–146, Jan. 2016, doi: 10.1002/jee.20111.
[13] D. C. Rice, J. M. Ryan, and S. M. Samson, "Using concept maps to assess student learning in the science classroom: Must different methods compete?," *J. Res. Sci. Teach.*, vol. 35, no. 10, pp. 1103–1127, 1998, doi: 10.1002/(SICI)1098-2736(199812)35:10<1103::AID-TEA4>3.0.CO;2-P.
[14] N. L. Miller, P. C. A. Conocimiento, A. J. Cañas, J. D. Novak, and M. Cognition, "Use of the Cmaptools Recorder to Explore Acquisition of Skill in Concept Mapping," in *Proc. of the Third Int. Conference on Concept Mapping*, Tallinn, Estonia & Helsinki, Finland, 2008.
[15] A. J. Cañas, L. Bunch, J. D. Novak, and P. Reiska, "Cmapanalysis: An extensible concept map analysis tool," *J. Educ. Teach. Train.*, 2013.
[16] G. Guest, K. M. MacQueen, and E. E. Namey, *Applied thematic analysis*. Sage Publications, 2011.
[17] V. Braun and V. Clarke, "Using thematic analysis in psychology," *Qual. Res. Psychol.*, vol. 3, no. 2, pp. 77–101, Jan. 2006, doi: 10.1191/1478088706qp063oa.
[18] J. Cohen, "A coefficient of agreement for nominal scales," *Educ. Psychol. Meas.*, vol. 20, no. 1, pp. 37–46, 1960, doi: 10.1177/001316446002000104.
[19] D. A. Regier *et al.*, "DSM-5 Field Trials in the United States and Canada, Part II: Test-Retest Reliability of Selected Categorical Diagnoses," *Am. J. Psychiatry*, vol. 170, no. 1, pp. 59–70, Jan. 2013, doi: 10.1176/appi.ajp.2012.12070999.