Sustainability coursework: student perspectives and reflections on design thinking

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Abstract

Purpose – The purpose of this study was to assess particular student outcomes when design thinking was integrated into an environmental engineering course. The literature is increasingly promoting design thinking for addressing societal and environmental sustainability engineering challenges. Design thinking is a human-centered approach that identifies needs upfront.

Design/methodology/approach – In an undergraduate engineering course, *Design for the Environment*, students have begun to obtain hands-on experience in applying design thinking to sustainability challenges. This case study investigates the association between the use of design thinking and student creativity with sustainability design solutions. Student perspectives on their own creativity and future sustainable design practices as a result of the course were also investigated.

Findings – The findings were favorable for design thinking, being associated with a significant difference and medium-to-large effect with regards to solution novelty. A qualitative analysis showed a positive association between design thinking and students' perceptions of their creativity and future anticipated sustainability practices. Using a content analysis of reflective writings, students' application of design thinking was assessed for comprehensiveness and correctness. A two-week introductory design-thinking module and significant use of in-class active learning were the course elements that most notably impacted students' use of design thinking.

Practical implications – This case study preliminarily demonstrates that application of design thinking within an environmental engineering course may be associated with beneficial outcomes related to creativity and sustainability.

Originality/value – A review of the literature did not uncover studies of the use of design thinking for undergraduate socio-environmental challenges to promote creativity and sustainable-practices outcomes, although the literature has been calling for the marrying of these two areas.

Keywords Design thinking, Creativity and innovation, Reflection, Sustainable design, Environmental engineering education

Paper type Research paper

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1. Background and relevant literature

Solving today's complex environmental and societal engineering challenges will require the current generation of students to possess a creative skillset and mindset. Design thinking, a human-centered design approach, has recently gained traction as a creative approach for solving societal and environmental sustainability problems. In *Design for the Environment*, an undergraduate engineering course in sustainability, students have begun to apply the design-thinking process to sustainability-related engineering challenges over the past several semesters. Specifically, a design-thinking approach was introduced to the course in the fall of 2017 and was used again in the fall of 2018. Enhancing student creativity was a primary driver and reason for incorporating the design-thinking process as an underpinning of the course. This paper describes a case study of the associated changes in students' creativity and anticipated future sustainability practices with this course modification. The modification was motivated and enabled by the instructor's experience at Stanford's *d. school* during the summer of 2017. In addition, feedback from the fall 2016 semester suggested the use of more hands-on innovation and design activities, including in-class use of the school's makerspace. The resulting course re-designs involved activities during class that enabled students to gain hands-on experience with the five stages of the design-thinking process. They ultimately applied this process to a semester-long sustainability design challenge, which was assessed for creativity. By applying a case study approach with multiple forms of assessment, the following research questions of interest were investigated:

RQ1. Does an environmental engineering course using the design-thinking process impact student perspectives regarding their future sustainability practices?

RQ2. Does an engineering course using the design-thinking process impact students' creativity, including perceptions of their own creativity?

RQ3. To what degree do student reflections indicate comprehensive and correct application of the design-thinking process to a sustainability design project?

A combination of surveys and focus groups were used to gather student perspectives on design thinking, including perceived changes in their creativity and future anticipated sustainability practices. The goal in using design thinking was to enhance the creativity of students' solutions to sustainability challenges of a socially and/or environmentally responsive nature. The creativity of the design solutions before (vs with) the use of design thinking was assessed using two instructor evaluations. Further, reflective writings were used to assess students' execution of the design-thinking process with the design challenges. The following literature-based subsections provide additional background on the components and objectives of the course, including the design-thinking process, sustainable development, creativity (and its definition), reflective thinking and active learning.

1.1 Design-thinking process

Integration of the design-thinking process to the course was intended to enhance student learning and creativity. The design-thinking process is a five-stage, iterative process consisting of empathizing and/or interacting with the customer or user, defining the problem, ideating or brainstorming solutions, low-resolution prototyping and testing of the prototype (Hasso Plattner Institute of Design at Stanford, 2020). Designers often iterate on the latter steps to improve the solution. Thus, design thinking encompasses the spaces of inspiration, ideation and implementation (Brown and Wyatt, 2010). The design-thinking method developed at Hasso Plattner Institute was chosen because the instructor attended the teaching and learning studio workshop at Stanford's *d. school*, in which she developed the course redesign idea to implement in the undergraduate classroom in the context of sustainable engineering to teach students how to design more creatively and sustainably. This method is being adopted by design firms and various companies in the USA. However, this approach parallels other methods such as the British Design Council's Double Diamond Method, which is also empathy-centric, iterative and diverges/converges on solutions (Design Council, 2020).

Design thinking is a human-centered approach to innovation that identifies human and societal needs and integrates them with technological and economic feasibility (Brown, 2020). It has been labeled as a participatory or co-design approach, in which designers typically or ideally closely interact with (or even become embedded in the lives of) the people who will eventually use the product or service, and this approach has been directly linked to socially responsible design (Melles *et al.*, 2011). In *Design Thinking for Social Innovation*, Tim Brown, Chief Executive Officer of IDEO and high-profile advocate of design thinking, calls on designers to "[. . .] observe the actual experiences of smallholder farmers, schoolchildren, and community health workers as they improvise their way through their daily lives" (Brown and Wyatt, 2010, p. 33). Brown has actually called for the use of design thinking with the world's greatest challenges, including the needs of the poor and healthy food systems (Brown, 2020). Brown has taken the stance that an interdisciplinary team using a design-thinking approach is well-positioned to solve complex problems involving social and environmental concerns (Brown and Katz, 2011).

1.2 Sustainable development and sustainability education

There is a globally recognized need to tackle today's challenges using sustainable practices and innovations. This is most notably outlined by the United Nation's Sustainable Development Goals (United Nations: Sustainable Development Goals, 2020), which outlines aggressive targets to be realized by 2030 in the areas of poverty, inequality, climate, environmental degradation, prosperity, peace and justice. Achieving these goals of ensuring availability and sustainable management of water and sanitation for all and ending poverty and hunger, for example, will require a new mindset that transcends that which created these challenges. We must therefore equip the current generation of students with the skills necessary to develop innovative sustainable solutions. To this end, the application of design thinking to complex social and environmental issues, as advocated by Tim Brown, was a primary instructional and learning objective in this course (Brown and Katz, 2011; Brown and Wyatt, 2010). With their semester-long sustainability projects, students were tasked with meeting the needs of the present but with a long-term focus on the needs of future generations as well as targeting a balance among social, economic and environmental/ecological interests (Fischer, 2015).

A compatible and symbiotic relationship between sustainable development and the design-thinking process has been suggested and discussed in the literature (Fischer, 2015). Design thinking has actually been identified as potentially transformative to societies for their sustainability-related challenges, and it is increasingly being applied in social, societal and environmental problem-solving (Chick and Micklethwaite, 2011). The promise inherent in applying design thinking to complex environmental and social problems has also been documented by others (Brown and Wyatt, 2010; Westley *et al.*, 2011). Businesses were first to embrace design thinking; however, nonprofits are starting to use design thinking for better solutions to social problems (Brown and Wyatt, 2010). The application of design thinking to sustainability science has been characterized as an untapped opportunity area that “has not been rigorously tried,” particularly given the urgency of problems in this interdisciplinary area (Fischer, 2015, p. 177).

In 2018, Case Western Reserve University in the USA launched its new Center for Engineering Action, which has a single focus on design for humanitarian problems, but with a human-centered design and engineering approach (Rouvalis, 2019). In fact, sustainability education is important internationally. For example, the University of Plymouth in the UK specializes in sustainability education through its Centre for Sustainable Futures. It formally supports curriculum innovation projects in sustainability education and actively conducts pedagogical research on sustainability education, including on its own curriculums at the university (Wyness and Sterling, 2015; University of Plymouth: Current Innovation Projects in Sustainability Education, 2020; University of Plymouth: Sustainability Education Research, 2020). In fact, the approach taken in *Design for the Environment* aligns with Plymouth’s guidance on sustainability education, in which active, participative, and outdoor/experiential methods are suggested (Wyness and Sterling, 2015; University of Plymouth: What is Education for Sustainable Development?, 2020). More specifically, critical reflection, project-based learning, use of campus as a learning resource, group learning, community engagement and creative thinking are suggested by the University of Plymouth (Wyness and Sterling, 2015; University of Plymouth: What is Education for Sustainable Development?, 2020). Thus, the use of design thinking in this course for addressing sustainability challenges is aligned both with calls from the literature as well as the initiatives of select academic leaders to use design thinking and active, creative, socially minded work for significant positive sustainability outcomes.

1.3 Creativity

Design thinking has become a method for driving student creativity and innovation, for teaching creative problem-solving, and for enhancing or rediscovering one’s creative confidence (Kelley and Kelley, 2012; Royalty *et al.*, 2014). One method for driving or rediscovering creative confidence is through *practice*, including breaking large challenges down into smaller ones and successfully completing each one (Kelley and Kelley, 2012). Interestingly, creativity has often been viewed as something that a person either does or does not possess (Stenger, 2018). However, studies suggest that creativity and thinking-outside-the box can be developed through training, for example, through the intentional capture of new ideas during brainstorming activities (Epstein and Phan, 2012; Epstein *et al.*, 2008; Stenger, 2018).

The literature has indicated the need for engineering curricula that fosters creative skills, as the development of divergent thinking skills is often missing from engineering courses (Daly *et al.*, 2014). For purposes of *Design for the Environment*, creativity was defined as a combination of novelty/originality and usefulness/value/feasibility, as also defined by others working in engineering education and design (Chulvi *et al.*, 2012; Genco *et al.*, 2012; Moss, 1966; Oman *et al.*, 2013; Sarkar and Chakrabarti, 2011). In managerial contexts, design thinking has been associated with innovation and creativity (Brown and Wyatt, 2010; Johansson-Sköldberg *et al.*, 2013).

1.4 Reflection

Reflecting on one’s actions is a desirable practice, as learning occurs through a combination of doing as well as reflecting on the doing, as described by Kolb’s experiential learning theory (Kolb and Kolb, 2009). Based on Schon’s theory of the reflective practitioner, reflection is particularly key for designers, as it provides them with skills needed for unstructured problem-solving (Schon, 1987). Schon described the “reflective conversation” that can occur between the designer and the design scenario, which may assist in deeper understanding of the problem (Adams *et al.*, 2003; Schon, 1987).

Reflection-on-action, which occurs after an activity when one is thinking and evaluating, was used in the present study as a means to document and assess students' application of the design-thinking process to their sustainability projects (Schon, 1987). The application of reflective writing to assess students' use of the design-thinking process was chosen after contacting Stanford's *d. school* (Personal communication, 2017, with *d. school* associates). In communicating with two associates there, they were not aware of an instrument to specifically assess student's execution of the five-stage design-thinking process, although reflective journaling was mentioned as a potential approach (Personal communication, 2017, with *d. school* associates). In a separate project, students at Stanford's *d. school* used a reflective assessment process known as reflection design practice (RDP) (Royalty *et al.*, 2018). With RDP, Stanford students used weekly reflective assessments to drive more in-depth understanding of design processes by reflecting on actual concrete artifacts created during design or project courses.

1.5 Active learning

To support and enable students' use of the design-thinking process for their semester-long design projects as well as respond to their desire for active learning, frequent practice activities during class were used. For example, after mini-lectures, students participated in group-based design sessions, activities and class discussions to develop creative solutions to sustainability problems using elements of the design-thinking process. Active learning is defined as anything students do in class in addition to listening to the instructor and taking notes (Felder and Brent, 2016). The theory and research have established the benefits and effectiveness of active learning in regard to problem solving, skills application, conceptual gains, in-class engagement and exam performance (Chi, 2009; Freeman *et al.*, 2014; Hake, 1998; Wieman, 2014).

2. Methods

2.1 Course context

The sustainable engineering course *Design for the Environment* is an annual 15-week, semester-long course of approximately 30 juniors and seniors that is open to undergraduates from any university major. Although the majority of enrolled students are civil or environmental engineering majors, the course has also attracted non-engineering majors, including environmental science and architecture students. It is an elective course offered by the Department of Civil and Environmental Engineering at a research-intensive university in the mid-Atlantic region of the USA. There are no specified pre-requisite courses; therefore, there are no expectations for pre-existing knowledge on sustainability or design, although some engineering students did have previous exposure to the engineering design process and design thinking via other courses.

The primary course learning objectives were to enhance students' creativity and innovation as well as their practice of sustainable engineering as they designed and evaluated products and processes. The strategies used to accomplish these learning objectives included specific instruction in and hands-on practice with the design-thinking process, which was used to ultimately drive a creative, innovative solution to a semester-long sustainability design challenge. The semester-long project served to engage students with sustainable engineering practices so they could apply what they learned in class to a current sustainability challenge. In the course overall, students learned product and process design practices for sustainability as well as about sustainability in general. Specifically, in addition to gaining first-hand experience with design thinking, students also learned about the sustainability topics of design frameworks, life cycle assessment, biomimicry, design for disassembly and toxicity and risk.

With the sustainability design challenge, teams consisting of three or four students engaged in the design-thinking process and applied the sustainability course content to develop a solution. Teams were formed based on student interest in the particular challenge. In addition to four project reviews throughout the semester, the final project submission included a 10-min oral presentation in the form of a pitch to mock investors (i.e. a panel comprised of 8-12 sustainability and design experts), a prototype and a one-page "leave-behind." Students used one page, in any form, to represent their final solution. Example project topics included:

- the built environment (e.g. transformation of a vacant space to integrate sustainability and/or to engage the community in sustainability);
- agriculture (e.g. reduction of food waste and inefficiency of irrigation or fertilizers);
- natural disaster relief (e.g. reduction of single-use items and excessive packaging while still providing the essentials of life); and
- recycling (e.g. pizza boxes).

Active learning was a key component of the course. In addition to engaging students in the learning process, many of the activities were developed to enable students to apply and practice the stages of the design-thinking process. For example, a module was developed to introduce the design-thinking process to students during the first two weeks of the course. This module allowed students to "live" the five stages of the design-thinking process by engaging in field work outside the classroom and reporting back for debriefing at the end of each class period. In addition to this introductory design thinking module, in-class activities on a given topic were designed to engage students in specific steps of the process. These sustainability-based modules contained interactive, hands-on exercises for in-class use and were developed by the instructor and teaching assistant. For example, for the topic of biomimicry, students spent an entire class period engaged in the ideation stage, culminating in a proposed solution to an engineering challenge inspired by their assigned organism (e.g. bee, biofilm or penguin). The first two homework assignments included video clips, readings and questions that allowed students to further engage in and learn about different aspects of the creative design process (e.g. opportunity statement development from guided observation). In-class readings, video clips and discussion aimed to break down preconceived barriers to creativity. Collectively, the activities were intended to empower students to think without constraints and to embrace failure, because it is through this process that students learn and innovative solutions are born. Additional details on the course changes can be found in a prior publication (Clark *et al.*, 2018).

2.2 Assessment methods

To assess students' perspectives on and execution of design thinking, various data collection methods were used within this case study of a sustainability engineering course, including surveys, focus groups and written reflections. Students' perceptions of their creativity and future sustainable career practices were obtained through surveys and focus groups. Using written reflections, students described their application of the design-thinking process to their semester design challenges. Surveys and written reflections were completed by students outside of class. The various questions were developed as a joint effort among the research team members, which consisted of both instructional and assessment personnel.

Two analysts, the project's assessment analyst and an environmental engineering PhD student with an instructional role, conducted qualitative content analyses of the collected data from two semesters using Microsoft Excel software given its flexibility (i.e. fall 2017 and fall 2018) to investigate the various research questions. Given the smaller class size (i.e. approximately 25 students per year), data from 2017 and 2018 were pooled for the results. Participation in the surveys, reflections and focus group was voluntary, although students could earn up to two additional percentage points for their participation. Although no students opted to do so, they could complete an alternative assignment to gain the extra two percentage points in lieu of participating. Approval for the collection and analysis of this data was granted by the University's Institutional Review Board.

2.2.1 Surveys. Surveys were administered to the students online using the Qualtrics software at the beginning and end of the course to assess student perspectives on design thinking and their perceived enhancement in sustainable practice and creativity. Each student was asked to enter his/her assigned code for each survey so the responses could be matched (i.e. paired) in a before-vs-after manner. The open-ended survey questions shown in below list from the end-of-the-term survey were content-analyzed. Similar questions were posed during the focus group and content-analyzed to triangulate the results.

End-of-term survey questions:

SQ1. What have you learned or been exposed to in this course that will enhance how you practice sustainable engineering in your future career?

Focus group questions: *FGQ1*. Describe any changes in your perceived creativity that you feel are a direct result of this course.*FGQ2*. Can you tell me about a specific experience in this course where your *design-thinking process* skills improved?*FGQ3*. What have you learned or been exposed to in this course that will enhance how you practice sustainable engineering in your future career?*FGQ4*. What do you think helped most in this course to develop your *design-thinking process* skills?:

SQ2. List the in-class activities, assignments, lectures, projects, etc. that most positively impacted your use or application of the design-thinking process (i.e. five steps) and a short description as to why.

2.2.2 Focus group. A focus group was conducted in the second-to-last week of the semester to gather students' perspectives on design thinking and any perceived changes in their creativity and future practice of sustainable design. Class time (i.e. 75 min) was used for this, with the analysts (i.e. the assessment analyst and environmental engineering PhD student) conducting the groups. The students were split into two groups, with the first group being interviewed during the first 45 min of class, and the second group during the last 45 min of class. A series of nine questions were posed, although the questions in below list are the focus of the present work because of their association (or association of their results) with design thinking. Students' responses were recorded using field notes and placed in electronic format for analysis. The results from these four questions were subsequently content-analyzed by the investigators. Recall that similar questions were asked on the post-course survey, serving to triangulate the results.

2.2.3 Qualitative analysis of survey and focus group responses. All survey and focus group responses were independently coded by each of the two analysts and then collectively discussed to assess inter-rater reliability (IRR) and reach consensus in the final codes assigned. IRR is a measure that indicates the level of initial agreement between two analysts who are coding data. Coding schemes were developed in an emergent manner by the analysts after initially reading through all student responses and identifying coding categories of interest in an inductive manner based upon the student response data (Neuendorf, 2002).

For the combined responses to *SQ1* and *FGQ3* about the practice of sustainable engineering in the future, one coding scheme was developed and used for the content analysis. The IRR associated with the use of this coding scheme was κ = 0.89, indicating strong agreement beyond chance. For *FGQ1* about changes in creativity, the IRR was κ = 0.77, also indicating strong agreement beyond chance with this coding scheme. Likewise, for the combined responses to *SQ2*, *FGQ2* and *FGQ4* about positive impacts on design-thinking skills, one coding scheme was developed, and the first-time IRR associated with this coding scheme was Cohen's κ = 0.86, also indicating strong agreement beyond chance (Norusis, 2005).

2.2.4 Design thinking reflections. The students were asked to complete a written reflection at two different points in the semester describing their application of the design-thinking process to their semester-long sustainability design projects. Although these reflections were not graded, they were intended to assess students' execution of the process in terms of comprehensiveness and correctness. Specifically, each student was asked to respond to the reflective prompt in below list at both the midpoint and end of the semester, although at the midpoint, they had not reached the latter stages of the design-thinking process yet. One identified limitation of these reflections, as with any method of self-reporting, is potential differences between the steps or actions that actually occurred vs those described or discussed in the reflections, with omissions in the reflections expected. These omissions may have been because of lack of detail or precision in the writing as well as issues with recollection, among other reasons. In addition, it is also possible that descriptions in the reflections were enhanced to include steps that may not have occurred.

Reflective question:

- Describe how you have applied or executed the five-step design-thinking process (i.e. empathize, define, ideate, prototype and test) in developing a creative solution to the sustainability design challenge in this course.

To analyze the reflections, the two analysts first reviewed all student reflections and developed a coding scheme in an emergent manner that primarily aligned with key actions or activities within the five stages of the design-thinking process – empathize, define, ideate, prototype and test (Hasso Plattner Institute of Design at Stanford, 2020; Neuendorf, 2002). The goal with the content analysis was to assess the comprehensiveness and correctness of the students' application of the design thinking process via their reflections as well as to identify the most frequently discussed design stages or elements. To be considered as fully *comprehensive* in terms of traversing the design-thinking process, each of the following key actions had to be specifically discussed in the reflection, as described in Table I:

- one or more categories from the Empathize stage;
- ID PROB category;
- one or more categories from the Ideate stage;
- PROTOTYPE category;
- TEST category;
- REFINE category; and
- ITERATION category.

Category description	Category code	Maximum comprehensiveness
Stage 1: Empathize		
Observe subjects in context	OBSERVE	At least one category necessary
Interview/talk with subjects; and conduct surveys	TALK	
Other (general) empathy research (apart from observing or talking)	RES	
Understanding needs, beliefs or values of subjects; acknowledgement that a solution must be useful or meet the needs (definition of creativity)	NEEDS	
Stage 2: Define		
Develop problem or design statement; and define/determine the challenge or problem	ID PROB	Necessary
Stage 3: Ideate		
Generate *many* solutions or ideas; brainstorming or other ideation techniques; and divergent thinking	IDEAS	At least one category necessary
Convergent thinking; and converging toward one idea	CONVERGE	
Stage 4: Prototype		
Develop a tangible prototype or sketch of design Necessary		PROTOTYPE
Stage 5: Test		
Testing performed and feedback received/obtained	TEST	Necessary
Feedback used to refine prototype/sketch	REFINE	Necessary
Additional		
Iterative activity described at any stage (excludes prototype refinement)	ITERATION	Necessary
Enhanced judgment via design thinking, including usefulness outside the course	JUDGE	
Application errors		
Process described appears sub-optimal (i.e. stages done out-of-order or otherwise incorrectly)	SUB	
Solution was implied in the problem/design statement	IMPLIED	

Table I. Coding scheme

These were the key actions that the instructor emphasized to the students in their application of the design-thinking process.

The coding scheme contains additional categories to characterize the reflections. For example, there is a category that captures students' feelings of enhanced judgment via experience with the design-thinking process (JUDGE). Conversely, there are categories that capture errors in students' application of the process. Specifically, there is a category for identifying the reflection as sub-optimal based upon the ordering of the stages or an otherwise incorrect execution of the process (SUB). There is also a category for implying the solution within the problem or design statement (IMPLIED), which should not be done because it evades considering the users' needs and getting to the root of the problem.

Using the coding scheme, all reflections were independently coded by each analyst, with subsequent discussion to assess agreement and reach consensus. As part of the emergent process of developing the coding scheme, the investigators continually refined it as they discussed their coding. The first-time IRR for the midterm and end-of-term process reflections combined was Cohen's κ = 0.80, which indicated strong agreement beyond chance (Norusis, 2005).

3. Results

3.1 Survey and focus group results

Given the inter-relatedness of the survey and focus group questions, the results from both methods are presented together in the following subsections to facilitate efficient discussion as well as to demonstrate similar, triangulated results from both data collection methods.

3.1.1 Design thinking associated with positive impacts on sustainable engineering practice. Students were asked about the impact of the course on their future practice of sustainability. This was done via both *SQ2* and *FGQ*3. Table II shows the results of the content analysis of the responses from both methods. Survey responses were received from 42 students (79 per cent of enrolled students), and only those categories mentioned approximately 25 per cent or more of the time via either survey or focus group are presented in Table II. In all, 87 per cent of enrolled students participated in the focus group, resulting in highly representative perspectives. The focus group "per cent of responses" in Table II were calculated using the total number of statements made in response to the particular question (which served as the denominator).

Interestingly, survey respondents most frequently associated the design-thinking process or user-centered design with this question (38 per cent of responses). Thus, over one-third of these open-ended survey responses identified the positive impact the design-thinking process will have on their future sustainable engineering practice. In addition, during the focus groups, students frequently stated (21 per cent of the time) that their exposure to design thinking and user-driven design will influence how they practice sustainability in their engineering careers in the future.

Over one-quarter of survey respondents (29 per cent) said the course led them to think about sustainability in a different way, including the many forms that sustainability takes as well as new interests or perspectives gained on sustainability. This was matched by the

Code	Category description	Survey: % of responses	Focus group: % of responses
DESIGN THINK/USER	Steps of the design-thinking process (listed individually or as a whole process); designing with the user in mind to solve a problem	38	21
FRAMEWORK	Sustainability frameworks (e.g. Twelve Principles of Green Engineering and Cradle-to-Cradle)	36	29
LCA	*Life cycle thinking/analysis* topic area, lecture and/or activities	36	8
DIFFERENT FORM	Students thought about sustainability in a different way after taking the class (e.g. the many forms of sustainability, new interests, new perspectives)	29	29
BIOMIMICRY	*Biomimicry* topic area, lecture and/or group activity	26	17

Table II. Content analysis: impacts on sustainable engineering practice focus group results, with 29 per cent of responses indicating this as well. The sustainability-specific topic areas and activities mentioned most frequently by survey respondents as influential to their future sustainability career practices were the following:

- sustainability frameworks (e.g. Twelve Principles of Green Engineering and Cradle-to-Cradle);
- life-cycle-assessment; and
- biomimicry, each mentioned by approximately one-fourth to one-third of survey respondents.

During the focus groups, the sustainability frameworks were also mentioned frequently (29 per cent) as was biomimicry (17 per cent).

3.1.2 Increases in student creativity are associated with design thinking. Focus group participants were asked to describe any changes in their perceived creativity resulting from the course (*FGQ4*). Interestingly, design thinking was mentioned or discussed in over two-thirds (68 per cent) of the statements made. This included any of the stages of the design-thinking process (i.e. empathize, define, ideate, prototype, test or refine) listed individually or as a whole process. Thus, students associated design thinking with changes in their perceived creativity. The following individual statements by focus group participants particularly demonstrate the impact of the course on their perceived creativity:

- I am more aware of my thought processes, specifically 1) get information, 2) develop a few solutions, and 3) test them, versus using just the first idea. I'm aware of "process."
- It's really about your user's creativity, as we are not experts. We rely on the creative thoughts of the users, and we must then build on their creativity. I had never thought of this before.
- I approach an issue/problem differently and think about more than one solution. I do more brainstorming than ever.
- Before this course, I thought creativity was something inherent or inherited. But, I now know it's a scientific method. This course is helping to grow my creative thinking.
- I don't focus on one solution right away. I consider: What are the possibilities?
- The various side projects with the steps broken down gave me direction. I learned it's OK to make as many mistakes as you want, as long as you are willing to fix them. I have more confidence in my creativity.

In addition to a post-course survey, a pre-class survey was also administered. Both surveys posed the following question on a five-point scale from strongly disagree to strongly agree: *I believe a person can learn to be creative*. Approximately 72.5 per cent of pre-survey respondents agreed or strongly agreed that a person could learn to be creative. On the post-survey, this percentage rose by five percentage points to 77.5 per cent. Although this suggests the impact of the course on students' assessment of their creativity, a paired-samples t-test did not show this difference to be statistically significant ($p = 0.36$). The non-parametric test version (i.e. related-samples Wilcoxon signed rank test) corroborated this result ($p = 0.39$). The effect size, which is a measure of practical significance, was small with Glass' delta = 0.19 (Lakens, 2013). An example of an impactful student survey response related to learning to be creative was as follows:

> I would define creativity as something that can be learned now. I didn't think I was creative before I came into this class and now I know by going through the design steps that I can think of anything and create anything.

3.1.2.1 Project scores. Direct assessment results suggested that design thinking may be associated with a significant increase in student creativity. The students' semester-long design projects from 2017 to 2018 vs 2016 (i.e. *with* vs *without* design thinking, respectively) were evaluated by the instructor and teaching assistant for creativity. In alignment with the definition of creativity used in this work as well as by others (as discussed in Section 1.3 on Creativity), the rubrics of Genco *et al.* and Moss, which assess creativity based on novelty and usefulness/value, were applied (Genco *et al.*, 2012; Moss, 1966). The instructor and teaching assistant were chosen as the evaluators of the projects because they were the only two individuals who were:

(1) experts in all aspects of the projects and their assessment domains;
(2) engaged with all teams throughout the semester, including the provision of intermediate feedback; and
(3) ultimately familiar with the evolution of the project and extent of engagement with the design-thinking process.

The evaluators independently graded the projects and then averaged their scores. Given the smaller class size (i.e. approximately 25 students per year), project data from 2017 and 2018 were pooled.

In comparing the results of the projects before the use of design thinking (2016) vs with the use of design thinking (2017 and 2018), the 2017-2018 semesters had the higher average adjusted scores for the novelty dimension (i.e. 0.56 vs 0.68, respectively, each with a standard deviation of 0.17). The maximum score that could have been achieved for the novelty dimension was 1.00. Given the small sample sizes (i.e. 7 projects prior to design thinking and 15 projects with design thinking), the non-parametric version of ANCOVA (i.e. Quade's test) was used, with the team's average pre-course grade point average serving as the covariate or control variable (Lawson, 1983; Quade, 1967). The difference in the novelty scores (2016 vs 2017-2018) was statistically significant ($p = 0.031$). In addition, the effect size, a measure of practical significance, was medium to large, with Hedge's $g = 0.71$ (Lakens, 2013). This preliminarily suggests the use of design thinking may be associated with enhanced novelty (both practically and statistically). This enhancement occurred without negatively impacting usefulness or value, as the average usefulness score increased with the use of design thinking, although not significantly so ($p = 0.695$) and with a small to medium effect size ($g = 0.43$). Assessing creativity in this manner (i.e. separately analyzing novelty and usefulness) has been done by others (Genco *et al.*, 2012).

3.1.3 Hands-on, in-class design activities drive students' design-thinking skills. Students were asked about activities or experiences in the course that had positive impacts on their design-thinking skills development and use (*SQ1*, *FGQ1* and *FGQ2*). Survey responses were received from 44 students, or 83 per cent of enrolled students. Table III shows the results of the content analysis of the survey and focus group questions, organized by the categories developed for the coding scheme. Only those categories which were mentioned approximately 25 per cent or more of the time via either method (i.e. survey or focus group) are presented in Table III.

As shown in Table III, the introductory class sessions on design thinking (first two weeks of the course) and the use of active learning in the course to support design thinking were the two most-frequently mentioned categories in the survey responses as the factors

Code	Category description	Survey: % of responses	Focus group: % of responses
INTRO	Initial class sessions or activities (at start of course) that introduced the five-step design thinking process	41	21
ACTIVE LEARNING	Active learning and practice occurred; hands-on work; students were actively involved in learning and/or "walking through" the design thinking stages	41	19
PROJECT	Semester-long sustainability design project	39	15
BIOMIMICRY	*Biomimicry* topic area, lecture and/or group activity	32	8
BRAINSTORM	Brainstorming or ideation activities, including *Sticky Notes* ideation activities	27	10

Table III. Content analysis: positive impacts on design thinking

that positively impacted students' application of the design-thinking process (41 per cent of responses each). Likewise, the two-week introductory class sessions were most frequently mentioned during the focus groups as the experience that enhanced or developed students' design-thinking skills (21 per cent). During these first two weeks, students were introduced to and given the chance to actively practice, or "walk through," the various stages of the design-thinking process. Students in general appreciated the active learning they encountered in the course and felt it supported their use of the design-thinking process (41 per cent of survey responses; and 19 per cent of focus group responses). With the active learning, practice and hands-on work occurred, and students actively "walked through" the design-thinking steps. It appears that these approaches and activities may be important when teaching courses in design thinking.

Not unexpectedly, the final project was also a top-mentioned category in the survey responses in positively impacting students' use of design thinking (39 per cent), as it required application of all five stages. Biomimicry was the most frequently mentioned sustainability topic area for positively impacting students' use of the process, identified by 32 per cent of survey respondents. This may indicate the usefulness of incorporating biomimicry in this type of course, keeping in mind that biomimicry was also identified as impactful to the students' future practice of sustainability (Table II). Brainstorming and ideation activities were also having positive impacts on students' application of design thinking (27 per cent of survey responses).

3.2 Design thinking process reflection results

In assessing the responses to the process reflections, 32 midterm and 39 end-of-term reflections were completed, representing 60 per cent and 74 per cent of enrolled students, respectively. Upon analyzing the students' design-thinking reflections from the end of the semester for comprehensiveness and correctness of their design processes, 4 out of 39 reflections (10.3 per cent) discussed all 7 of the necessary stages or elements from Table I for fully comprehensive application of the design-thinking process. These included elements specific to each of the five stages as well as the occurrence of iteration anywhere in the process (excluding prototype refinement). A breakdown of the reflections in terms of the number of elements discussed for maximum comprehensiveness is given in Table IV. Although 18 per cent of the reflections discussed none or just one of the necessary elements, 53.9 per cent discussed four or more of the seven critical elements. Thus, the majority of student reflections on the design-thinking process were moderately comprehensive (at a minimum), which was a desirable result demonstrating general alignment of positive design-thinking outcomes with actual use of the design-thinking process.

It was also of interest to assess the occurrence within the reflections of each of the categories in the coding scheme. Table V describes these frequencies in both the end-of-term and midterm reflections. For the midterm reflections, the students had not yet reached design stages four or five (prototype and testing) with their semester design projects; therefore, those categories were not discussed in the midterm reflections. In addition, not all teams had reached the ideate stage at the midterm point as well. However, all teams had completed stages one and two (empathize and define) by this point in the semester.

The percentages of reflections that described each of the first three stages of the design-thinking process were close in value at each point in time (i.e. midterm vs end-of term). For example, the empathy stage was discussed in about three-quarters of the reflections (i.e. 74 per cent and 81 per cent of end-of-term and midterm reflections, respectively). Slightly more midterm reflections (vs final reflections) described problem identification in the define stage (78 per cent), possibly because it was a current or recent activity for the students at the time of the midterm reflection. Approximately two-thirds of the reflections discussed the ideation phase (i.e. 67 per cent and 72 per cent of end-of-term and midterm reflections, respectively). These percentages indicate that at least two-thirds to three-quarters of reflections discussed

Necessary elements discussed	% of reflections
All (7)	10.3
Six (6)	15.4
Five (5)	17.9
Four (4)	10.3
Three (3)	10.3
Two (2)	17.9
One (1)	15.4
Zero (0)	2.6

Table IV.
Description of end-of-term reflections

Elements discussed	% of end-of-term reflections (n = 39)	% of midterm reflection (n = 32)
One or more categories from empathy stage	74	81
ID PROB category (from define stage)	67	78
One or more categories from ideate stage	67	72
PROTOTYPE category	54	Stages not reached by course midterm
TEST category	54	
REFINE category	21	
ITERATION category	41	0
JUDGE category	10	13
SUB category	15	19
IMPLIED category	0	3

Table V.
Discussion of elements in the design process reflections

these necessary stages of the design-thinking process and were encouraging from an instructor's point of view.

In the final reflections, 21-54 per cent of students discussed the PROTOTYPE, TEST and REFINE categories. It is possible that students may have run out of time, or the nature of the project may have factored in. Interestingly, ITERATION was not discussed in the midterm reflections, although it could have been. For the end-of-term reflections, however, ITERATION was discussed in 41 per cent of them, which was a welcome finding. In both the midterm and end-of-term reflections, any sub-optimal execution of the design-thinking process was evident in under 20 per cent of the reflections, and the solution was implied in the problem statement in only a very small number of midterm reflections (3 per cent).

4. Discussion

Design for the Environment, a civil and environmental engineering course that is part of the sustainability course offerings in the department, was significantly modified so students could apply the design-thinking process to sustainability design challenges. Recent literature has called for the use of design thinking in addressing today's complex societal and environmental sustainability issues; thus, this research is relevant and timely.

Based on a combination of assessment results from three semesters of *Design for the Environment*, the design-thinking process was associated with positive and/or significant outcomes related to student creativity, perceptions of creativity and future sustainability practices. Thus, the findings preliminarily indicate that design thinking may be associated with enhanced student creativity and sustainability outcomes. This preliminary finding is important, as a review of the design-thinking literature concluded a lack of experimental studies involving design thinking (Razzouk and Shute, 2012). This review identified an opportunity to conduct experimental studies in this area, including those focused on various student learning outcomes (Razzouk and Shute, 2012). If faculties are preparing the next generation of engineers for enhanced creativity and sustainability practices and are able to begin documenting significant outcomes in these areas using methods such as design thinking, faculties as educators are responding well.

This pedagogical and assessment approach can be used by other instructors interested in using design thinking to investigate and potentially promote student creativity with sustainability design challenges involving societal and environmental problems. Systematic introduction to and practice with the design-thinking process during the initial portion of the course as well as subsequent active learning involving the design-thinking steps were important to students' application of the process to their semester sustainability challenges. Given these favorable initial outcomes, ongoing research with design thinking in sustainability engineering education is being pursued, including an investigation of gender-related issues.

4.1 Limitations

Despite the use of data collected across three semesters of the course, the sample size is small because of restrictions on the course's enrollment and the assessment of team-level (vs individual) projects. The smaller sample size has prompted preliminary conclusions at this point regarding the association of design thinking with creativity and sustainable outcomes. However, the smaller sample size was accounted for by using non-parametric statistical methods. Additional future research will allow more definitive conclusions to be drawn.

In considering the survey and focus group protocols used, several wording changes will be made so the questions are slightly less leading for the next iteration of the research. For example, for *SQ1*, the word "enhance" will be changed to "change." Another source of bias may result from the different project topics having different characteristics, including the potential for more or less creative solutions. However, the project groups were formed based on student interest; therefore, each group member was equally motivated by his/her project topic.

5. Summary and conclusions

A case study research approach was applied to investigate several questions related to changes in students' creativity and anticipated sustainability practices associated with design thinking. Based on a qualitative content analysis of survey and focus group responses, students' perceptions of design thinking, in particular its impact on their creativity and future sustainable engineering practices, were favorable. Survey respondents most frequently identified the design-thinking process as the aspect of the course that will positively impact their sustainable engineering practices in the future. The specific sustainability topic areas and activities mentioned most frequently by survey respondents as being influential to their future career practices were the sustainable design frameworks, life-cycle-assessment and biomimicry, each mentioned by approximately one-fourth to one-third of survey respondents. The focus group participants freely mentioned design thinking in approximately two-thirds of responses about perceived changes in their creativity as a result of the course. A statistically significant increase in the project novelty score was found with design thinking, along with a medium-to-large effect size, which indicated practical significance of the result. Based on a qualitative content analysis of student reflections on their use of design thinking, the majority of reflections were (at a minimum) moderately comprehensive in their discussion of the prescribed design stages. Thus, students' application of the design-thinking process generally aligned with the positive direct and indirect assessment outcomes observed. The two-week, introduction-to-design-thinking course module and the notable use of active learning during class were the two most-frequent positive impacts on students' application of design thinking, each associated with over 40 per cent of survey responses. Thus, it appears that these two approaches and activities may be important when teaching sustainability courses in design thinking.

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