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Assessment of Using Design Thinking to Foster Creativity in an Undergraduate Sustainable Engineering Course

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ABSTRACT

Addressing complex global sustainability challenges requires a creative mindset, yet current engineering curriculum does not facilitate development of student creativity. Design thinking, as defined by the Hasso Plattner Institute of Design at Stanford, is a human-centered, creative design methodology that can be used to foster cognitive aspects of student creativity. This empirical study evaluates the impacts of a design thinking process on student performance, including product creativity as a group measure and students' individual perspectives of creativity within the context of sustainable engineering. Data was collected in three semesters of an undergraduate sustainable engineering course, two of which implemented design thinking. Student performance on sustainability design challenges was evaluated across four dimensions: novelty, usefulness, sustainability, and application of a design thinking process. Self-reported assessment methods, including pre- and post-surveys and focus groups were used to assess students' perceptions of their creativity. Groups of students exposed to design thinking had significantly higher design project scores across the novelty, sustainability, and design thinking dimensions. This suggests that design thinking may enhance the quality of solutions to sustainability challenges in terms of creativity and sustainable design. Individually, students became more confident about their ability to be creative as a result of this course and the

unique characteristics of design thinking. Collectively, our results suggest that incorporating design thinking into the engineering classroom facilitates student development of a creative cognitive process, enabling innovative solutions to complex engineering and sustainability challenges.

INTRODUCTION

The next generation engineer is faced with developing solutions to increasingly complex global challenges, such as poverty, hunger, access to clean water, climate, and economic crises, many of which are outlined in the United Nation's Sustainable Development Goals ("United Nations Sustainable Development Goals", 2019). Innovative, rather than incremental, solutions are needed to address these challenges, which require a shift toward a creative mindset. Creativity is not traditionally emphasized in the undergraduate engineering curriculum nor integrated with critical thinking and problem-solving skills (Benson, Becker, Cooper, Griffin, & Smith, 2010; Charyton, Jagacinski, Merrill, Clifton, & DeDios, 2011; Cropley, 2015; Daly, Mosyjowski, & Seifert, 2014; de Vere, 2009; Felder, 1988; Huntzinger, Hutchins, Gierke, & Sutherland, 2007; Mahboub, Portillo, Liu, & Chandraratna, 2004; Razzouk & Shute, 2012). In fact, industry leaders in the United States have identified a shortage in the number of engineers qualified to address societal challenges, specifically noting the lack of creativity and spirit of innovation among engineering graduates despite being technically competent (Benson et al., 2010; Cropley, 2015; de Vere, 2009; Felder, 2012; Huntzinger et al., 2007). Sixty-five percent of engineers in the workforce agree that today's engineers need to be more creative and innovative to be globally competitive (Charyton et al., 2011; Taurasi, 2007). Additionally, the Accreditation Board for Engineering and Technology (ABET) has highlighted the need to promote creativity in design and enhance open-ended problem solving ("Criteria for accrediting engineering programs, 2020–2021", 2019, p. 4.). In fact, ABET defines engineering design as an "iterative, creative, decision-making process that involves identifying opportunities, developing requirements, performing analysis and synthesis, generating multiple solutions, evaluating solutions against requirements, considering risks, and making trade-offs for the purpose of obtaining a high-quality solution" ("Criteria for accrediting engineering programs, 2020–2021", 2019, p. 4).

Design thinking, as defined by the Hasso Plattner Institute of Design at Stanford (commonly known as the d.school), is one such methodology that specifically addresses the creativity void left by the traditional engineering design process and other design paradigms taught in undergraduate engineering courses. Conventional design paradigms are rooted in a reliable, safe, and "prove it" mode of analytical thinking, while design thinking incorporates explicit elements related to creativity to help develop intuitive thinking and a creative mindset (Dam & Siang, 2021; "Design thinking bootleg", 2021; "Get started with design thinking", 2021). In this study, we report on the integration of a five-stage design thinking approach into an undergraduate sustainable engineering course, *Design for the Environment*. Here, we integrate human-centered design with sustainability, which both share elements around social design, and suggest that human-centered design is itself a key step in designing sustainability. We combine multiple assessment methods to fill the gap in assessing two aspects of student creativity as a result of design thinking, including the creativity of solutions to a sustainability design challenge (i.e., product creativity) and student perspectives of their creativity (i.e., personal creativity). Our results suggest that design thinking enhances solutions to sustainability design challenges in terms of creativity and sustainable design, and further, students become more confident in their ability to be creative. Finally, the study outlines a pedagogical approach to engineering design that instructors can adopt to enhance and assess students' creativity, presented here within the context of complex engineering and sustainability design challenges.

BACKGROUND LITERATURE

Emphasizing Creativity in Undergraduate Engineering Education

There are a limited number of university-level engineering programs that explicitly and effectively incorporate creative problem solving into classroom instruction (Daly et al., 2014; Dym, Agogino, Eris, Frey, & Leifer, 2005). The prevailing current engineering curricula are composed of traditional lecture- and textbook-based pedagogy that foster passive learning and further, drains students' excitement for creative problem-solving (Cropley, 2015). For example, when measuring the creativity of solutions generated for an open-ended design problem on the basis of originality and usefulness of the solution, freshmen were found to generate more original solutions than senior engineering students, while there was no difference between freshman and senior measures of usefulness (Genco, Hölttä-Otto, & Seepersad, 2012). Even after going through the program and acquiring more discipline-specific knowledge, the senior engineering students were less creative (Genco et al., 2012). Traditional engineering curricula focuses on the basic science of engineering and application of scientific principles to methodically solve technological problems in a well-understood, straightforward manner, without significant opportunity for students to learn through design or to develop and refine creative aptitude (Cropley, 2015; de Vere, 2009; Dym et al., 2005; Mahboub et al., 2004; Razzouk & Shute, 2012). Traditional emphasis has been on fundamental content, memorization, and inside-the-box-thinking that lacks applicability to students' careers and skills development to tackle future challenges (Huntzinger et al., 2007).

Problem framing (i.e., identifying the need and defining the problem) and divergent thinking skills (i.e., exploring many potential problems in the problem space and many solutions through idea generation in the solution space) are missing from most engineering curricula (Daly, Yilmaz, Christian, Seifert, & Gonzalez, 2012; Daly et al., 2014; de Vere 2009; Dym et al., 2005; Felder 1988). Rather, students are often given a defined problem to solve in a particular way (convergent in nature) as opposed to open-ended problems with multiple solutions that are better for stimulating creativity and resemble real-world engineering design (Adams, Kaczmarczyk, Picton, & Demian, 2007; Doppelt, 2009; Dym et al., 2005). This deprives students of the opportunity to exercise their creativity, define the problem themselves, and develop the expertise needed to devise a unique solution from the ground up (Cropley, 2015; Huntzinger et al., 2007). Both divergent and convergent modes of thinking are critical because both are needed to solve complex societal challenges (Dym et al., 2005; Felder, 1988) and it is well established that the highest levels of creativity require both modes of thinking (Luenendonk, 2015). Creativity is not embedded in the engineering design process; in fact, simply engaging in the phases of a design process (through project-or design-based learning which are components of many engineering design courses) does not necessarily mean creativity will be employed (Daly et al., 2014). Rather, creativity is a cognitive skill (i.e., recognizing a problem exists, producing ideas, evaluating possibilities, and drawing conclusions to lead to a solution) that can be developed through deliberate and intentional practice and implemented at the designer's discretion (Daly et al., 2014).

Furthermore, there is a need to assess creativity in engineering courses to ensure student creativity is being developed and/or enhanced under the employed creativity-enhancing technique (Charyton & Merrill, 2009; Daly et al., 2014; Felder, 1988; Felder, 2012). Evaluating creativity as a learning outcome is a valuable part of engineering design education and can be used to encourage students to think about creativity, become more aware of their own creative processes, and consciously work towards creative design (Chiu & Salustri, 2010; Charyton & Merrill, 2009; Daly et al., 2014). For example, engineering undergraduates who received feedback after taking a creativity assessment had higher quality and more creative designs on a design task than students who did not (Cropley & Cropley, 2000). Despite the recognized importance of implementing creativity-enhancing pedagogies and a variety of established approaches by which to empirically evaluate creativity (*vide infra*), there remains a void in practice (i.e., engineering instructors do not actually employ these methods to evaluate student creativity as part of course learning outcomes in engineering courses) (Chiu & Salustri, 2010; Daly et al. 2014; Genco et al., 2012). This is likely due to the fact that emphasis on skills such as creativity is new and the need for assessment is not yet fully realized.

Studies of first-year design courses showcase their implementation of design-based projects and pedagogical approaches, but either focus more on technical aspects or do not present student creativity outcomes (Daly et al. 2014; Doppelt, 2009). Most studies are qualitative and exploratory in nature, lacking quantitative assessment, analysis, and interpretation (Badke-Schaub, Roozenburg,

& Cardoso, 2010; Daly et al., 2014). Daly et al. (2014) studied seven undergraduate and graduate engineering courses that had creativity as a learning objective, and noted a lack of creativity assessment. Originality, a critical component of most product definitions of creativity, was not explicitly assessed in six of the seven courses (Daly et al., 2014). This demonstrates a common lack of alignment between learning goals and assessment of creativity. Finally, some studies that include creativity evaluation do not associate the assessment with a specific course component or learning outcome (i.e., they simply measure creativity as in the case of validating a new creativity evaluation method with other established creativity measures) (Charyton and Merill 2009; Charyton et al. 2011). Despite existing evaluation methods, student creativity is not being evaluated nearly enough in the engineering classroom which would also help to inform best practices for enhancing creativity.

Design Thinking as a Pedagogy to Enhance Student Creativity

Design thinking emphasizes a human-centered design methodology that was practiced and popularized by the global design consultancy firm, IDEO ("History," n.d.), and is now used by many organizations for strategic innovation and organizational management (Badke-Schaub et al., 2010; Brown & Wyatt, 2010; Korsunski, Hoffman, Gormon, Angst, & Roeschmann, n.d.; Schell, n.d.). At IDEO, there is no single definition of design thinking ("Design thinking defined." n.d.; "How do people define design thinking?" n.d.). Many definitions of design thinking exist, and it is continually being re-conceptualized, although there are some key attributes that many agree are cornerstones to a design thinking approach (e.g., understanding human needs, reframing problems in human-centric ways, using a complex set of skills, processes, and mindsets, embracing ambiguity, thinking without judgment or fear of failure, etc.) ("How do people define design thinking?" n.d.; "Shape the future with design thinking." n.d.; "What is design thinking?" n.d.). IDEO defines design thinking as "an idea, a strategy, a methodology, and a way of seeing the world"; "a way to solve problems through creativity"; "a process for creative problem solving"; "a set of both mindsets and design-based activities that foster the collaboration required to solve problems in human-centered ways" ("Design thinking defined." n.d.; "How do people define design thinking?" n.d.). It is an emerging design methodology also being integrated into undergraduate engineering curricula to enhance design creativity and offer a rich experience to prepare students for their future engineering careers (Royalty, Oishi, & Roth, 2014).

Stanford's d.school is the leading university of teaching design thinking. University educators can specifically engage in the methodology through the d.school's Teaching and Learning Studio (Moore, 2018), where workshops are held for instructors to learn about and develop strategies for implementing design thinking into their educational initiatives. A five-stage process is commonly used for introducing students to design thinking (Dam & Siang, 2021), which can then evolve into a broader approach or mindset for more experienced designers (Carter, 2016). This initial five-stage process, more recently referred to as the five "modes", emphasizes reimagining the user experience in place of a problem-solution paradigm and includes students empathizing with the user's needs through interaction (e.g., engagement, immersion, observation, interviewing) where the goal is to build a mental model of the user's beliefs, values, and behaviors by gaining insights into the user ("An introduction to design thinking process guide," n.d.; Dam & Siang, 2021; "Design thinking bootleg", 2021; "Get started with design thinking", 2021). This stage or "mode" is then followed by students defining their own authentic problem, brainstorming and assessing solutions in a divergent-convergent thinking loop, creating simple prototypes that incorporates the developed mental model of the user, testing the prototypes to gain new insights into the user, and iteratively ideating, prototyping, and testing to converge upon the best solution ("An introduction to design thinking process guide," n.d.; Brown & Wyatt, 2010; Dam & Siang, 2021; "Design thinking bootleg", 2021; "Get started with design thinking", 2021). A more experienced designer will likely deviate from using this recipe-like, hierarchical five-stage process and develop their own sets of mindsets, behaviors, and intuition for implementation, focusing instead on flexing eight core design abilities (e.g., navigating ambiguity, learning from others, synthesizing information, rapidly experimenting, etc.) (Carter, 2016).

Generally, the steps within the d.school's methodology are closely intertwined with the concept of creativity – recognizing a problem exists, producing ideas, evaluating possibilities, and drawing conclusions to lead to a solution. Design thinking involves in-depth analytical and creative cognitive processes, which may nurture students' critical thinking and creativity skills (Badke-Schaub et al., 2010; Dym et al., 2005). This authentic, hands-on, and immersive process provides students with regular opportunities to refine these skills, offers open-ended problem solving with the potential for infinite solutions, incorporates the complexity of the engineering design process, and contains the most common elements lacking in current curricula but found in real-world engineering design (i.e., problem framing, talking to stakeholders, and divergent thinking) (Atman, Adams, Cardella, Turns, Mosborg, & Saleem, 2007). A study that compared engineering students' use of the engineering design process with that of practicing engineers found that experts spent more time gathering information and defining the problem than students (Atman et al., 2007). The findings suggest that preparing students for successful careers requires exposure and experience in identifying and adequately scoping a problem before developing the solution (i.e., the first two stages of design thinking that are uniquely emphasized). The experimentation-based nature of design thinking further encourages students to redefine problems through observation not simply 'asking' for solutions, question assumptions, become comfortable with sensible risk taking, tolerate ambiguity, think without judgment or fear of failure, and build creative confidence and self-efficacy (Cropley, 2015; Dym et al., 2005; "History," n.d.; Kelley, 2020), all of which are unique traits of the d.school's design thinking methodologies. It is important to note that many approaches to design exist, even under the same name of 'design thinking' that have been used to foster creativity and describe design thinking beyond the methodologies defined by the d.school. In this work, and hereafter when we refer to design thinking, we focus specifically on the five-stage design thinking model proposed by the d.school, since this model was taught in the study classroom after participating in the d.school's Teaching and Learning Studio (Moore, 2018).

Despite the unique characteristics inherent to design thinking that may impart creativity, more research and classroom-based empirical studies formally showcasing its positive impacts is needed, especially upon longer-term immersion in design thinking (e.g., a semester-long project) (Chulvi, Mulet, Chakrabarti, López-Mesa, & González-Cruz, 2012; Korsunskiy et al., n.d.; Razzouk & Shute, 2012; Royalty et al., 2014; Schell, n.d.; Thoring & Müller, 2011). Specifically, there is a lack of performance-based assessments of design thinking skills and resulting creative student performance (Korsunskiy et al., n.d.; Daniel Hall, personal communication, August 8, 2017; Leticia Britos Cavagnaro, personal communication, October 15, 2017; Razzouk & Shute, 2012; Royalty et al., 2014; Schell, n.d.). Some studies have focused their evaluation on just one element of design thinking processes, mainly ideation, to assess creative outcomes (Chulvi et al., 2012; Daly et al., 2012), even though all steps likely play a role in developing student creativity. For example, teaching students to understand user needs and frame the problem may increase creative production, as usefulness is also an important dimension of creativity. Testing and receiving user feedback can also help students converge on more creative solutions. The nature of design thinking itself - being experimentation-based and encouraging students to think without judgment or a fear of failure - is likely to enhance student creativity. To evaluate design thinking as a creativity-enhancing process in the context of sustainable engineering, we borrow some of the established strategies from studies evaluating creativity in engineering. The following section discusses the many literature-based definitions of creativity and metrics proven useful for evaluating creativity in engineering education to inform the approach that we developed and apply in our study.

Definitions of Creativity and Methodologies for Assessment

Some theories of creativity focus on the 4P's (i.e., person, process, product, and press) as one model to explain and understand creativity ("4Ps of creativity," 2016; Rhodes, 1961). Creativity can be considered a complex combination of personal qualities such as abilities, attitudes, awareness, feelings, and motivation (person), cognitive skills (process), and environmental factors such resources and support (press), all of which lead to the creation of the product and/or outcome. Each of these aspects – the creative worth of a product, the creative thinking process of an individual, and an individual's creative personality – can be measured (Candy, 2013; Genco et al., 2012), although measurement of one may or may not correlate to the measurement of the others (Bandura, 1997; Charyton & Merrill, 2009; Cropley & Cropley, 2000; Genco et al., 2012). Often, metrics focused on the process or the individual's creative personality are referred to as indirect measures of creativity, as opposed to metrics focused on the outcomes that are direct measures (Genco et al., 2012). Creativity has also traditionally been viewed as an innate trait that one either possesses at birth or is otherwise immutable (Stenger, 2018). This implicit belief is maintained by many students today, despite extensive research that suggests an individual's creativity can be enhanced through teaching creative design (Guilford, 1950; Candy, 2013; Chiu & Salustri 2010; Epstein, Schmidt, & Warfel, 2008; Hewet, 2005), and can impede development of a creative skillset (Stenger, 2018). Thus, the degree of openness a student demonstrates in honing their creativity further comprises a part of the personal dimension of creativity.

Some definitions of creativity address a single or subset of the 4Ps. For example, Torrance (1979) defined creativity as related to creative cognition. Specifically, he considers the ideas that people generate in response to a stimulus, which are assessed by fluency (number of relevant ideas), flexibility (number of different categories that ideas span), originality (number of infrequent ideas), and elaboration (number of ideas expanded with details). Methods like the Torrance Tests of Creative Thinking (TTCT) measure creative thinking capabilities, important for creative performance, but do not include criteria for the other Ps. Other definitions of creativity focus on the products generated as a result of the other Ps (Candy, 2013; Genco et al., 2012), which is acknowledged as the least studied factor in the field of creativity ("4Ps of creativity," 2016). The most common definition of product creativity is a combination of novelty (i.e., new, original, surprising, or not resembling something formerly known) and useful (i.e., appropriate, functional, effective, or valuable), both evaluated using numerical scales (Candy, 2013; Charyton & Merrill, 2009; Chiu & Salustri, 2010; Chulvi et al., 2012; Clark, Stabryla, & Gilbertson, 2018; Cropley, 2015; Genco et al., 2012; Moss, 1966; Sarkar & Chakrabarti, 2011; Sternberg, 2012). In engineering, where the task is to develop effective solutions, the outcome or product tends to be of greater interest (Charyton & Merrill, 2009; Genco et al., 2012) and is suitable for empirical research on creativity. In our study, we evaluate the creativity of students' solutions to semester-long projects (i.e., 'product', which is a group measure in this study) based on novelty and usefulness. Additionally, students' creative personal qualities (i.e., 'person', which is an individual measure in this study) are measured through evaluation of their self-reported beliefs about creativity and their creative confidence.

METHODOLOGY

Research Purpose and Questions

The present study evaluates how design thinking, incorporated into an undergraduate sustainable engineering course, influences the creative capabilities of undergraduate engineering students. We accomplish this by evaluating (i) students' developed solutions (i.e., the product, a group measure of creativity) to a sustainability design challenge after being exposed to a five-stage design thinking process compared to unexposed students and (ii) student perspectives on their creativity development (i.e., personal qualities, an individual measure of creativity) using mixed assessment methods. Qualitative and quantitative methodological approaches were applied to investigate the following research questions:

RQ1: Does exposing students to design thinking increase the creativity of group solutions to a sustainability design challenge (i.e., product creativity)?

RQ2: Does a design thinking focused engineering course influence students' individual perspectives of their own creativity (i.e., personal qualities)?

Participants

Participants consisted of 79 students across three semesters enrolled in *Design for the Environment*, an upper-level undergraduate engineering course in sustainability at a public university in the United States. *Design for the Environment* is one of four sustainability courses offered in the Civil and Environmental Engineering department that students can use to fulfill their sustainability requirement. It is a 15-week course consisting of approximately 25–30 juniors and seniors each term, with the majority of students majoring in civil or environmental engineering (CEE) and the minority consisting of other engineering disciplines or students from the arts and sciences (e.g., environmental science, architecture). There are no pre-requisite courses and therefore students are not expected to enter the course with knowledge on sustainability concepts or design thinking. Combined, 47 (59%) of the students identified as male and 32 (41%) of the students identified as female, with shifts in the majority gender occurring from semester to semester. Sixty-seven (85%) of the students were White, six (7.5%) of the students were Asian, and two (2.5%) of the students were each Hispanic, Black, and a member of multiple races. This composition remains approximately consistent across semester.

Course Content

The course covers fundamental concepts, including sustainability design frameworks, toxicity and risk, product life cycle and systems thinking, life cycle assessment, end-of-life-management and design for disassembly, and energy in relation to sustainability. Recently, the course content was structured around a d.school approach to design, where the core skills associated with design thinking, including empathizing, re-imagining the user experience, unpacking interviews and uncovering insights about the users, and building mental models of the user, are taught in the classroom during a two-week initial crash course (Figure 1). The instructor implemented

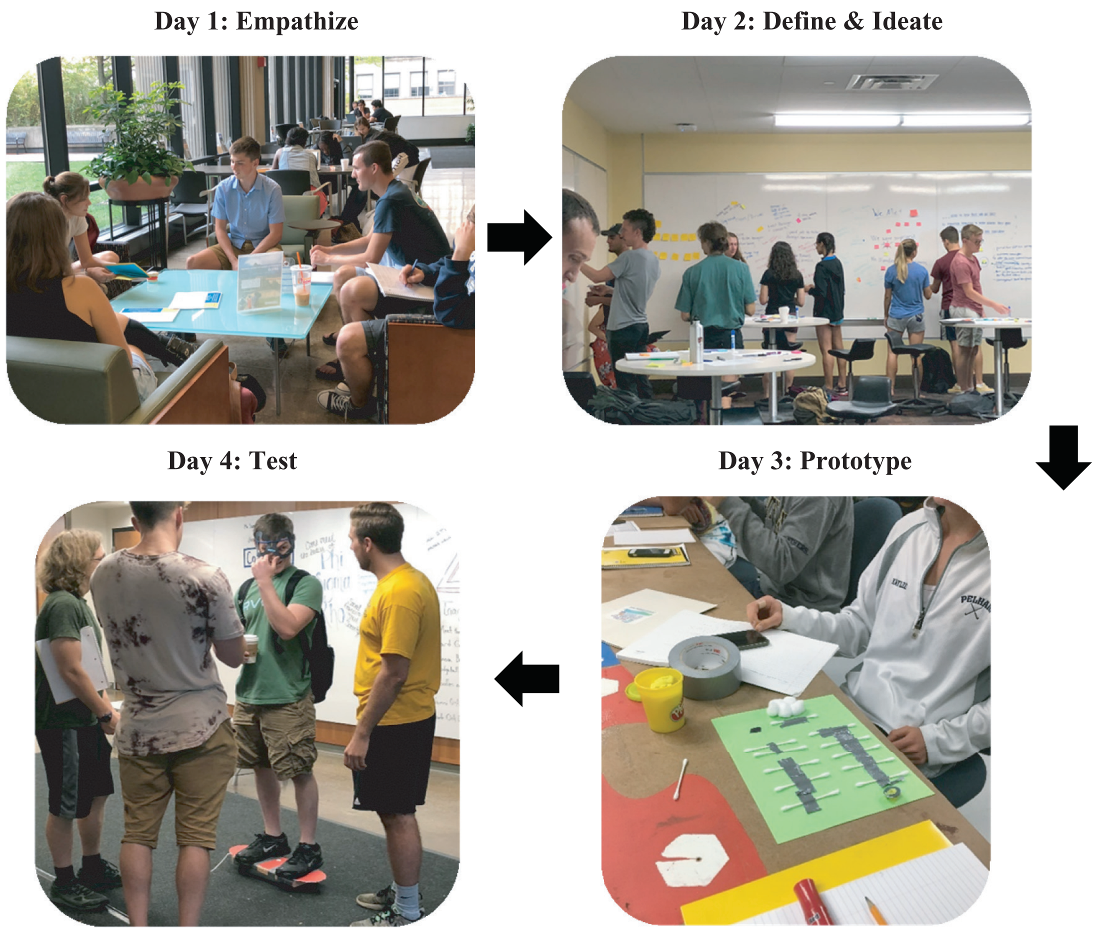

Figure 1. Students are introduced to design thinking through a two-week crash course on a five-stage design thinking process, where students experience or 'learn-by-doing' the five stages of design thinking first-hand through fieldwork. Their first field work assignment involves working in groups to interview people outside the classroom about a particular topic related to life-long learning ('emphasize' stage). During the next class session, they "unpack" their interviews using a POV (point-of-view) statement to frame a design opportunity for the 'define' stage. This leads to in-class brainstorming activities for rapid generation of solution ideas in the 'ideate' stage using whiteboards and sticky notes. The third and fourth class sessions are held in the school's makerspace so students can perform low-tech 'prototyping' and 'testing' with people outside the classroom to receive feedback on their design.

a) b)

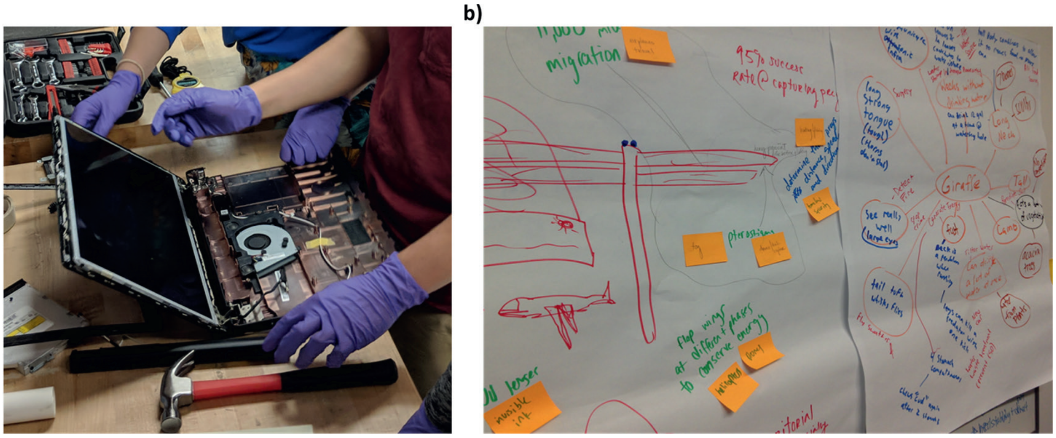

Figure 2. Examples of sustainability modules that incorporate in-class design sessions and exercises to engage with each stage of design thinking. a) End-of-life management and design for disassembly is a sustainability topic included in the course for students to think about end-of-life considerations with respect to the initial design of a product. It is taught through an in-class activity in the school's makerspace in which student groups disassemble obsolete electronic products, including phones, DVD players, laptops, headphones, and cameras, using a household toolkit. The students track their steps as they disassemble the products and categorize the types and recyclability of the materials encountered. b) Biomimicry design is another sustainability topic covered in the course where student groups research an organism's unique traits to create design principles and apply them to solve a mini-sustainability challenge of their choice. Here, students iterate through research, problem definition, ideation, and evaluation stages of design thinking.

this approach during the fall 2017 after attending a faculty workshop hosted by the d.school's Teaching and Learning Studio (Moore, 2018). Additional exercises to engage with each stage of the process are incorporated into hands-on sustainability modules throughout the course (Figure 2), which were either included for the first time or significantly revamped from the fall 2016 semester when the instructor taught this course without a design thinking approach (note: formative data assessment from the fall 2016 semester serves as a comparison dataset). A semester-long, group design project serves as a cornerstone of the class and as a way for students to apply course content to tackle a sustainability challenge, which remained the same between the semesters except that a design thinking methodology was required to be carried out in the design projects during the fall 2017 and 2018 semesters. Additionally, traditional lecture was minimized in 2017 and 2018. Homework assignments, in-class readings, video clips, and discussion further supplemented in-class material, providing the opportunity to reinforce and apply concepts from class. Short primer exercises and improvisational warm-up techniques were also integrated throughout the course in 2017 and 2018 to encourage students to think without judgment nor have a fear of failure. In 2017 and 2018, the course was taught in a collaborative-style, flexible classroom that included movable tables and whiteboards on all walls of the room. Additional details on the course changes and examples of sustainability modules can be found in our prior publication (Clark et al., 2018).

The centerpiece of the course is a semester-long project in which groups of three or four students are tasked with developing a novel and useful solution to their self-defined problem statement. The student groups are formed based on student interest in the challenge options; all students submit their ranked, top three options and the teaching team forms groups to maximize student interests. The general topic areas include, 1) providing clean drinking water, 2) reducing food waste, 3) more efficient use of water and fertilizer in agriculture, 4) recycling (e.g., pizza boxes), 5) aiding in survival after a natural disaster, 6) biomimicry inspired outdoor equipment, 7) reduction of noise pollution caused by lawn equipment, and 8) re-designing or re-purposing a vacant city space in a way that facilitates community engagement with green engineering and sustainability. These sustainability challenges are intentionally open-ended, enabling students to engage in an entire design thinking process, including the first two stages, particularly empathy to define the opportunity and find insights about users that might drive a solution in sustainability. Evidence of project development is submitted through four written deliverables, one-on-one meetings with the course instructor and teaching assistant, an interim presentation, and a practice final presentation, each of which provides formative feedback to the student groups. Given the heavy emphasis on empathy in the course, students are specifically required to document the ethnographic approaches used and their unpacked findings from the empathy stage in the written deliverables as well as present on this aspect in their final presentations. Examples of ethnographic methods used by the student groups and insights gained during the empathy and problem definition stages are presented in Table 1. Class time in the form of prototyping work days in the school's makerspace is allotted for the groups to work on their project and get additional feedback. The project culminates in a formal 10-minute oral presentation in the form of a pitch to a panel of mock investors (i.e., a panel comprised of 8–12 sustainability and design experts). Students are required to have a prototype, which could range from a mock-up, CAD drawing, vision board, or a physical object, that demonstrates the function of their solution and a leave behind in which students use one page to represent their final solution in any way they desire. Examples of the ideation, prototype, and testing stages as carried out by the students are presented in Table 2. Students' creative outputs are shown in Figures 3 and 4.

Table 1. Summary of the empathizing and problem definition stages students took to build a mental model of the end user/stakeholder in their application of the design thinking process for their sustainability design challenges. Ethnographic methods applied, insights gained, and students' defined problem statements were pulled from the students' project deliverables and final presentations.

Sustainability challenge area	Ethnographic approach	Insights gained after empathy stage	Problem statement iterations	Final problem statement
Repurposing vacant city space	Interviewed local, lifelong residents of the Beechview neighborhood, engaged with schoolchildren and teachers (e.g., 5th grade teacher and principal at Beechwood Elementary), members of the Beechwood Parent Faculty Association, executive director of Pittsburgh History and Landmarks Foundation	Students are lacking engagement with the outdoors and nature, i.e., there is a disconnect between kids and nature and they don't spend enough time outdoors. Students and community members alike have great difficulties in naming basic organisms in the ecosystems that they coexist in, e.g., a student didn't know a particular flower was called a rose. Children are a priority in the community, and they need a safe place to play. The centerpiece of the Beechview community is Beechwood Elementary, which is close to the vacant lot. Bringing different cultures together and encouraging community bonding is important as various cultures co-exist together in the community. Beechview has recently become a melting pot of families from various ethnicities, with a strong Latino presence. There is no historical center in the community and the local history of the community is important. Educational benefits are important to the residents of Beechview, including learning English, experiential learning about nature, sustainability, and transportation, and encouraging life-long learning for everyone in the community.	Repurpose the lot on Cape May Avenue to facilitate the community as a location to engage with one another, explore their surroundings, and encourage learning. Design an area that encourages families to venture outdoors. Design a space that allows the members of the neighborhood to deepen their individual roots and unify together as one. Design a space that allows the community to feel safe and inspired by nature. Design a space that helps residents feel safe by sharing a common space. Design a space where children can learn from being outdoors.	Design a safe community space that unifies the community members together while providing a place where children can learn from being outdoors.

Table 1. (Continued)

Sustainability challenge area	Ethnographic approach	Insights gained after empathy stage	Problem statement iterations	Final problem statement
		The area is attracting younger residents. Pittsburgh's light rail system is a big part of Beechview's economy. Problems in Beechview: tension in diverse community, declining business, escalating crime rate and drug usage, increase in poverty level, middle-to-low-income area		
Recycle pizza boxes (contaminated cardboard cannot be recycled)	Interviewed pizza shop owners and pizza consumers to re-imagine the experience of ordering a pizza; survey dissemination (100+ responses received)	Learned what consumers value in their pizza box experience, the qualities important in a pizza box deemed as 'normal use' (e.g., cost, ease of use, durability, heat, absorbance, etc.), and consumers' recycling practices (e.g., 40% recycle, 60% discard) 60% of respondents did not know that pizza boxes are rendered non-recyclable when contaminated with grease. Learned how many pizza boxes pizza shops go through in a typical weekend, cost of the box, etc. Users want something easier to take apart and dispose of, and note it is hard to store really big boxes in their fridge	Reduce number of unrecyclable pizza boxes. Reduce number of pizza boxes that get soaked by grease and cannot be recycled. Reduce total number of pizza boxes that are rendered non-recyclable or non-compostable through normal use.	Reduce total mass of pizza boxes that is rendered non-recyclable or non-compostable through normal use.

Table 2. Summary of the ideating, prototyping, and testing stages as part of a design thinking process being applied in student groups for their sustainability design challenges. Information was pulled from the students' project deliverables and final presentations. Note: the ideation column highlights only students' top ideas for which they completed an alternatives assessment.

Sustainability challenge area	Ideation – divergent process	Ideation – convergent process (and insights gained after user feedback)	Prototype	Testing	Insights gained after testing prototype	Final design with function
Repurposing vacant city space	Method – whiteboard to create concept map of ideas, that resulted in the identified top three ideas: Transportation museum on the history, development, and technical aspects of the Pittsburgh light rail system and preceding modes of transportation that served the community "Deep Roots of Beechview" treehouse – inspired by the residents of Beechview who have planted their family roots for generations. The idea is a string of tree houses at different heights connected by a system of bridges and containing games and puzzles to serve as an experiential, nature-oriented educational learning space for students and other community members. Nature center – an indoor and outdoor educational facility for kids and community members to learn about plants, gardening, and sustainability initiatives	Alternative assessment using multi-criteria decision analysis informed by community member and student input for assigning rankings and weights of criteria: – safety – social impact (remain a place where people can celebrate their unique backgrounds) – sustainability/ environmental awareness impact – economic feasibility – accessibility – promote bonding/ unity within the neighborhood Identified top choice: Deep Roots treehouse	Mood/vision board of a community tree house (Figure 4). The group brought representative items of numerous features of the treehouse.	Items were shared with multiple classes at Beechwood Elementary (Imagineers and Lego clubs) and teachers, asking for their opinions and their own ideas in the form of a discussion and letting them draw. This helped narrow down which amenities of the treehouse were most desirable. Surveyed Pitt students on what events they'd like to participate in	Outdoor recreation (e.g., rope course, field for games/sports, adventure, slides, tire swings) could be incorporated later Outdoor classroom – visiting location near the school during school hours would make learning more fun. Community could host performances here too – useful and engaging for many different age groups. This was well-received. Gardening and local plant/animal education – educate children about plant species/local wildlife in the area and gardening to learn to grow their own food. Could be integrated as part of the science curriculum. Sustainability incorporation – ideas included recycling drives, being solar powered, hosting workshops (e.g., arts and crafts event with recyclables) Learning theater with technology access and movie screening/presentation viewing – seemed counter to the goal of being outdoors. Would also need electricity to power.	"Deep Roots of Beechview" treehouse - string of tree houses containing an outdoor classroom, incorporating sustainability, and having a focus on gardening and plant/animal education to function as as a safe space for kids to learn, play, and engage with nature, while bringing the entire community together and uplifting principles of sustainability and green engineering.

Table 2. (Continued)

Sustainability challenge area	Ideation – divergent process	Ideation – convergent process (and insights gained after user feedback)	Prototype	Testing	Insights gained after testing prototype	Final design with function
Recycle pizza boxes (contaminated cardboard cannot be recycled)	Method – whiteboard to create concept map. Each group member chose their top two ideas, which were combined to generate the following: Liner: spray or paper-like material that would be applied or added to absorb grease or act as a barrier. Allows the box to be recycled. Modular: separating the box into detachable parts resulting in a reusable or recyclable top and removable, compostable bottom. Reusable box/pizza pocket/ Flexibox: multi-use box design that could be reusable and recycled at the end of its life; made of silicone or another flexible material. Origami wax paper box that folds to fit in your pocket	Alternative assessment using multi-criteria decision analysis informed by consumer input for assigning rankings and weights of criteria: – consumer/supplier ease of use, adoption – cardboard saved – recyclable, compostable, reusable – heat transfer – structural integrity – absorbance, cost, – storage/shipping functionalities Chose liner to move forward with	Compressed sheet of bamboo, pulp, and corn cob acting as different materials for the liner	Tested grease absorbance with different amounts of a bamboo composite, tested mixing bamboo, paper pulp, and corn cob for binding properties (Figure 3a) Tested use with pizza consumers	A 5:2:1 mass ratio of bamboo:corn cob: paper pulp was optimal to trap oil while still remaining bound together. Users felt removing the liner was easier than having to wash a box or tear off the bottom of the pizza box. Users would also willingly compost the liner, but this relies on the user and not everyone has the means to do so. They liked that their day-to-day pizza box use was not interrupted.	Composite, laminate bamboo absorbent liner with a bioplastic barrier sandwiched in between layers to function as a grease absorbent that is compostable while allowing the pizza box itself to be recycled (Figure 3b)

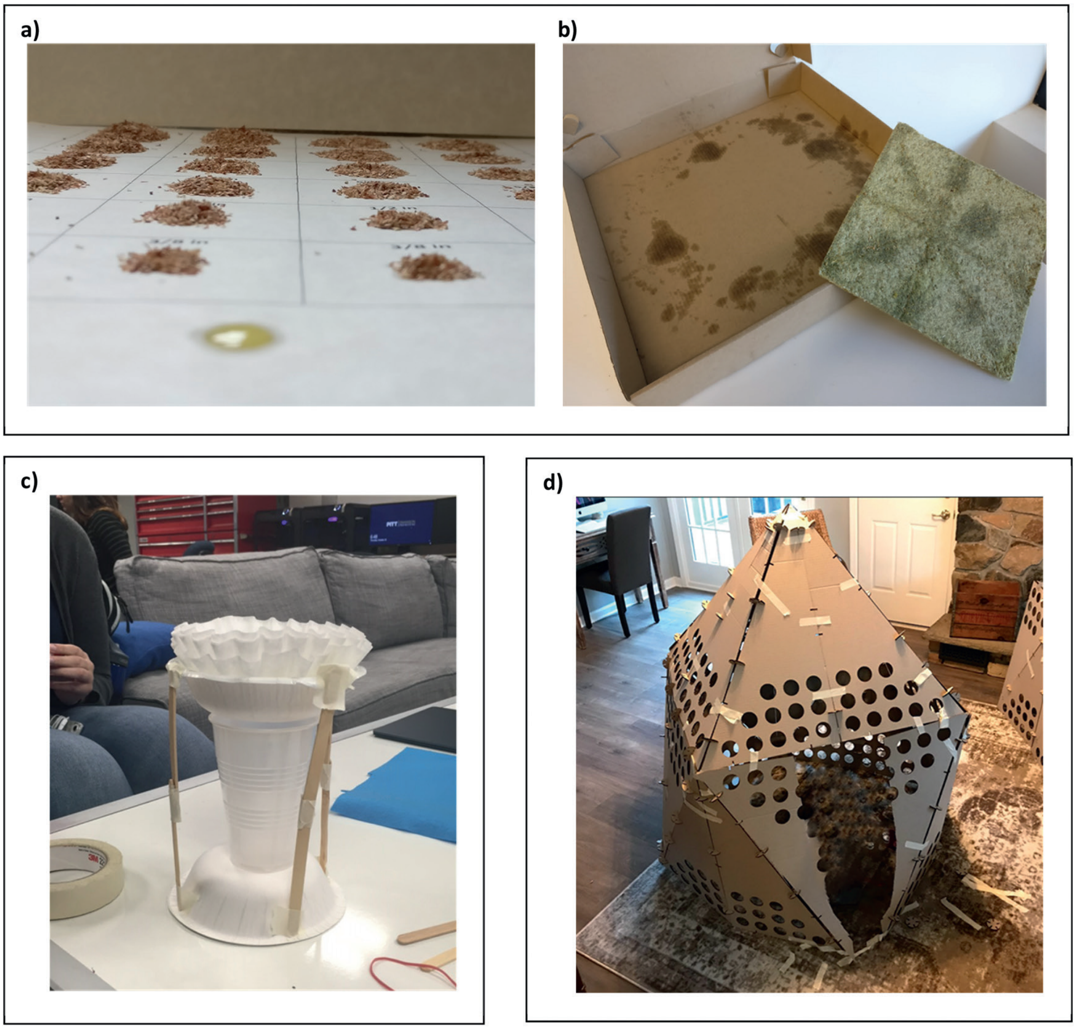

Figure 3. Examples of students' creative solutions to sustainability design challenges. a) Testing grease absorbance with different amounts of a bamboo composite and b) demonstrating their final prototype of a compostable, bamboo absorbent liner added to a pizza box to capture grease and enable recycling of the cardboard. c) Prototype of a filtering tarp supported by a folding tent structure that acts as a water filter and rain catching device to aid in survival after a natural disaster. d) Lifesize testing of a team's proposed 'Trilaterals Fort Kit', an adaptable, multifunction, children's fort made from recycled Nike tennis shoes to inspire creativity and improve communication skills in children while simultaneously enabling a circular economy of Nike shoes, as part of the Nike Grind Materials Challenge.

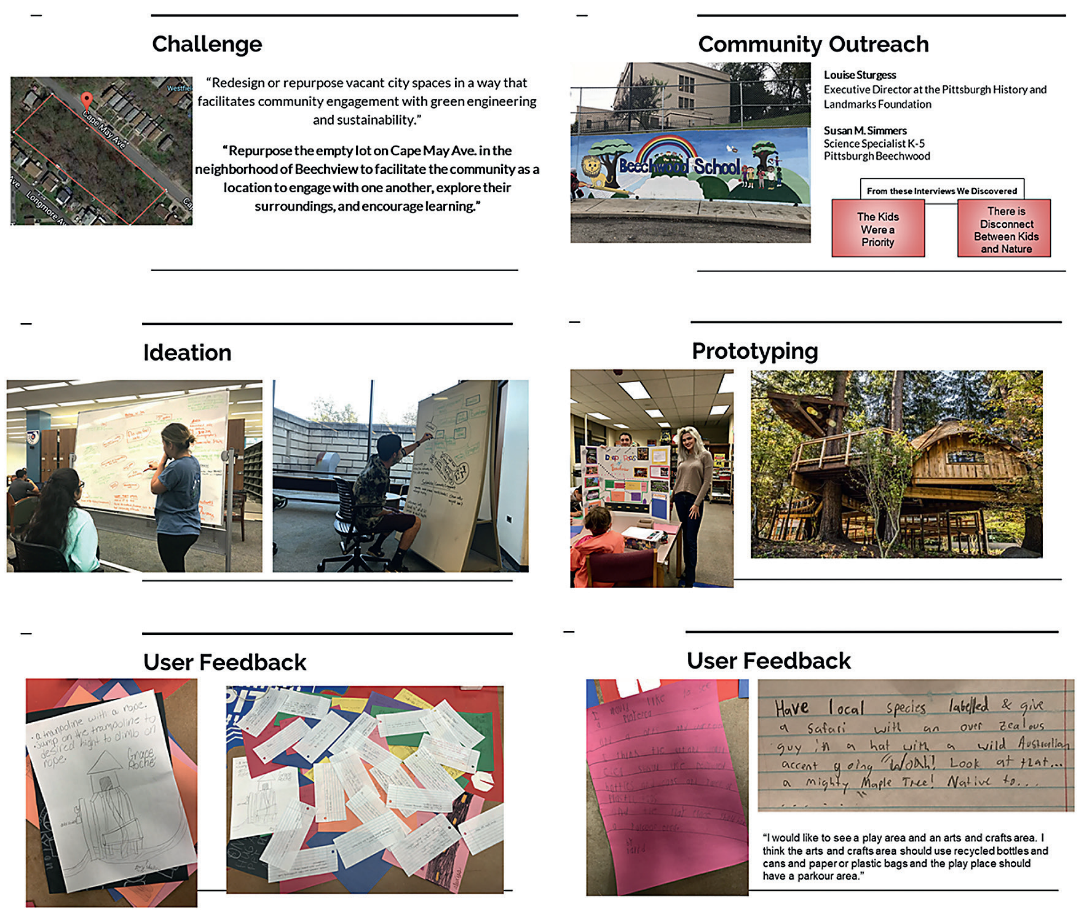

Figure 4. A student group's design thinking approach, taken from their final presentation, that led to the proposed idea of re-purposing of an empty parking lot in a Pittsburgh neighborhood to a community treehouse that hosts events to allow kids to re-connect with nature. Students incorporated feedback from teachers and students at Beechview Elementary school along each step of the design process.

Researcher Roles and Reliability

The instructor and an environmental engineering PhD student working as the teaching assistant implemented the course content. An assessment analyst and the teaching assistant served as the two data analysts working together to collect and analyze the data from two semesters (i.e., fall 2017 and fall 2018) to ensure reliability. The data analysts had no input into course grades beyond reporting to the instructor whether students participated in the surveys and focus groups. The instructor and the teaching assistant independently assessed the final projects from three semesters (i.e., fall 2016, fall 2017, and fall 2018) as they were knowledgeable across all domains of the projects, the evaluation criteria, and monitored the progress of all groups throughout the semester, including providing feedback on their project deliverables. Evaluation included a modified form of the consensual assessment technique (Amabile, 1982) with independent rating scales for the two-part creativity definition (novelty and usefulness). To avoid biasing final course grades, the instructor submitted grades prior to engaging with data in any manner.

Qualitative Data Collection on Individual Student Creativity Perspectives

An introductory script was given to the students explaining the research project. Student participation in the surveys and focus groups was voluntary, with the potential to earn an extra two percentage points towards the final grade in the course. If students did not want to participate, they could still earn the additional percentage points by completing an alternative writing assignment. To preserve student anonymity, the instructor assigned a randomly generated numerical code to each student to use when completing the surveys. This code system also enabled the analysts to link students' pre and post responses and their academic and demographic information. All surveys and focus group questions and the corresponding data analysis were approved by the university's Institutional Review Board (IRB).

Surveys were administered online at the beginning and end of the course outside of class time, and responses were exported into a spreadsheet for analysis. The focus groups were hosted by the two analysts during class time in the second-to-last week of the semester. Students were divided into two groups of 10–15 students each, with the first group participating during the first half of the class and the second group during the second half of class. The duration of each focus group session was 45 minutes. The two analysts posed several questions, probing more deeply into students' responses if needed, and took notes independently, after which they pooled them in an electronic format for analysis. Only one question has been analyzed for inclusion in this study. The instructor was not present during the focus groups to bias the responses given by the students.

Measures

Mixed assessment methods, including qualitative and quantitative approaches (Table 3), were used throughout the course to assess students' group project performance on sustainability design challenges as well as increases in and perceptions of their individual creativity. The methods included project assessments, surveys, and focus groups, as a way to triangulate the data.

Table 3. Overview of data collection and method of evaluation by semester.

Semester	Data Collected	Method of Evaluation
Fall 2016 Fall 2017 Fall 2018	Project assessment based on: • Group product creativity (novelty and usefulness) • Sustainability • Use of design thinking (RQ1)	*Quantitative:* Teaching team used the literature-based rubrics for the following dimensions: • Novelty (Genco et al., 2012) • Usefulness (Moss, 1966) • Sustainability (Watson et al., 2017) • Design thinking (modified version of Nagel et al., 2013) Statistical analysis of project scores to determine significant differences between Fall 2016 and Fall 2017–2018: ANCOVA
Fall 2017 Fall 2018	Pre- and post-surveys of individual student perspectives on creativity (RQ2)	*Qualitative:* Coding schemes were developed for open-ended questions and content-analyzed independently by two analysts *Quantitative:* Likert scale ratings Statistical analysis to compare pre- and post-survey student responses: Wilcoxon signed rank test
Fall 2017 Fall 2018	Student focus groups with a question pertaining to individual creativity perspectives	*Qualitative:* A coding scheme was developed for content analysis of compiled notes from focus groups related to one question and was analyzed for statements relating creativity to design thinking

Group project performance

As a direct, performance-based, quantitative measure, group projects were assessed based on four dimensions: 1) *novelty*, 2) *usefulness*, 3) incorporation of *sustainable* design principles, and 4) application of a *design thinking process*. Each dimension contributed one point to the overall score of 4 points. The design solutions from the fall 2016 (i.e., without a design thinking methodology) and fall 2017 semesters were evaluated simultaneously, the order of which was randomized in an attempt to enable a fair comparison and minimize bias between the two semesters.

Creativity of the student groups' final design solution was evaluated using the matrices of Genco et al. (2012) and Moss (1966), both of which assess product creativity on two dimensions – novelty and usefulness – using numerical scales to independently quantify them. It is important to note that creativity is taught and assessed differently in engineering disciplines. Since students from non-engineering disciplines comprised a minority of the class and were mixed in groups with engineering majors, we chose to apply the same definition of creativity to all groups when evaluating their solutions. We adapted Moss' scale (0–3) of usefulness, which compares the degree to which a product satisfies the requirements of the problem against a standard solution considered to be effective, by modifying the language of the score description away from an instructor-focused solution to include a focus on addressing the identified sustainable design challenge and demonstrating enhanced functionality (i.e., being well-suited to serve the intended purpose) compared to alternatives. Novelty was evaluated using Genco's rubric, a five-point scale, where the rater judges a solution as innovative or interesting versus common. The descriptions corresponding to each point has different meanings and is easy to distinguish their rankings, (e.g., common < somewhat interesting < interesting < very interesting < innovative).

The student groups' ability to engage in sustainable design was evaluated using a modified version of Watson, Barrella, Wall, Noyes, & Rodgers (2017)'s sustainable design rubric. Watson et al.'s rubric was developed based on the nine principles of sustainable engineering and three additional criteria addressing the economic dimension of sustainability. Together, this rubric considers social, environmental, and economic design criteria, which comprise the three pillars of sustainability. Each principle is divided into separate ideas, reaching a total of 16 design criteria to judge the sustainability content of student groups' design solutions. Slight modifications were made to the four design criteria falling under 'sustainable design tools' to reflect the content taught in the course and therefore applied to the project (e.g., replacing "incorporates life cycle analysis" with "considers the entire life cycle, not just the use phase"). Each criterion was rated (0-3) based on the level of applicability to a given project (i.e., potential points) and then how each group scored against the possible points. Student groups' design solutions were assigned a score of "0" earned points if the project did not incorporate the design criterion and a score of "1-3" given the level of criterion application. This rating system allows for differentiation between projects regarding how the student groups applied sustainable design principles. The instructor and teaching assistant agreed on the potential points before independently scoring the earned points. The final sustainable design score was determined by dividing the earned points by the potential points.

The design process rubric from Nagel, Pierrakos, & Nagel (2013) was adapted to guide assessment of the student groups' application and integration of a design thinking process in the development of their final design solutions. Modifications included adding empathy as a process stage being evaluated, combining the multiple prototype stages within their rubric into one, and assigning a rating scale (0–3) to each stage. The modified rubric is shown in Table 4. In Nagel et al. (2013), the rubric was used as a reflection tool for students to reflect on their engineering design process after their capstone project was completed. Here, the rubric was used to score student groups' application of each stage of design thinking, including empathizing with users/consumers/stakeholders and collecting information to build mental models of them, defining the problem, developing and assessing several ideas, creating a prototype of one idea, testing and refining their prototype with users, and iteration throughout the entire process.

Table 4. Modified rubric used to evaluate successful application and integration of a design thinking process in the development of the final product/solution.

Process Stage or Category Being Evaluated	0	1	2	3
Building Empathy	Did not observe, interview users or conduct empathy related research to guide solution	Worked from personal knowledge; interviewed people with similar experiences or who are familiar; Information learned was predictable; defined an expected problem/ opportunity; did not engage team in developing empathy. These observations, interviews, and empathy related research were not used to guide solution	Observed, interviewed, and/or conducted empathy related research and used it minimally to guide solution	Used a beginner's mindset; interviewed those with different/a range of experiences; uncovered unique or surprising insight; defined an unexpected/ game changing problem/ opportunity; resulted from synthesis of team discussion Significantly used these observations, interviews, and empathy related research to guide solution
Problem Statement Development	No problem statement	Problem statement is present, but only loosely used as a guide; no evidence of iterations and refinement	Problem statement is present and mostly used as a guide; some evidence of iterations and refinement	Problem statement is present and used as an overarching guide for solution development; demonstrated thoughtful refinement of focus as ideas matured.
Stakeholder Assessment or Market Analysis	Neither customer nor markets identified; non-analysis performed	Customers and market identified, but analysis not performed	Customers and markets analyzed but project was not guided by this analysis	Customers and markets analyzed and project is guided by analysis
Established Evaluation Criteria (Functions, Specifications, and Constraints)	Functions, specs, and constraints are not identified	Functions, specs and constraints are identified but not followed	Function, specs and constraints are identified and loosely followed	Functions, specs, and constraints to guide the entire design process
Generation of Multiple Concept Alternatives	One design considered, no evidence of brainstorming	Less than three designs considered, brainstorming evidence lacking	Three to six designs considered, brainstorming techniques employed and documented	Six or more designs considered, brainstorming techniques employed and documented
Structured Assessment of Concept Alternatives	Singly considered design chosen or no structured assessment applied	Assessment is unstructured or predetermined concept chosen	Structured assessment does not thoroughly vet alternatives	Structured assessment thoroughly vets alternatives
Iteration and Selection of a Concept	No iteration applied or single concept considered	Minor iteration applied to the chosen design	Design iterated but no further vetting of the design is performed	Design iterated and the new design is fully vetted
Prototype Generation	No evidence of prototypes generated	A prototype was developed; represents at least part of the solution	Multiple prototypes developed to represent at least part of the solution	Multiple prototypes developed, representing all solution components/functions, and developed at different stages of the solution development
Testing and Refinement	Testing and refinement was not performed	Prototypes tested but feedback was not implemented into solution refinement	Prototypes tested but feedback used minimally in solution refinement	Prototypes tested and feedback used in solution refinement/ ultimate implementation

Table 5. Pre- and post-survey (S) and focus group (FG) questions analyzed in this work related to students' individual beliefs about creativity.

SQ1. How do you define creativity?
SQ2. Rate the extent to which you agree with the following statement: I believe a person can learn to be creative.
SQ3. Rate the degree to which your ability to function creatively increased or developed as a result of this course.
FGQ1. Describe any changes in your perceived creativity that you feel are a direct result of this course.

Individual student beliefs about creativity

Baseline data on individual student perceptions of creativity was collected using a pre-survey, including their definition of creativity (free response) and implicit beliefs about their ability to learn to be creative (five-point Likert scale). Students were asked to define creativity themselves to provide insight into how they understand and view creativity, as part of their awareness and personal qualities dimension of creativity (one of the 4P's of creativity). Additionally, by having students identify their own definitions of creativity and use that definition to assess themselves on creativity, we were able to account for any differences in understanding creativity resulting from student major. At the end of the course, these same questions were posed in a post-survey to assess changes in student perspectives. Students were also asked to rate the degree to which they thought their ability to function creatively increased or developed as a result of this course (five-point Likert scale). The analysts posed a similar question during the focus group around students' perceived individual creativity for the purpose of triangulating and establishing the validity and reliability of the data from the surveys. These questions are summarized in Table 5.

Data Analysis

Quantitative group project performance analysis

To directly assess the association between the use of design thinking and students' group performance, group project scores on the sustainability design projects were compared for the semester where design thinking was not taught (fall 2016) and was incorporated (fall 2017 and 2018). Scores from the teaching assistant and instructor were averaged and used as the final score for each dimension being measured. Since each dimension had a different number of possible points given its specific rubric, each dimension score was normalized to one by dividing it by the number of possible points. Combining the dimensions, the maximum project score for each group was four points. Given the small sample sizes (i.e., 7 projects prior to design thinking and 15 projects with design thinking), establishing normality with certainty was not possible and therefore, a more conservative approach to statistical analysis was performed using the non-parametric version of ANCOVA

Table 6. Coding scheme used to content-analyze students' definitions of creativity.

Category Code	Description
NOVELTY	Originality; newness
USEFUL	Value, functionality, good or actual solution
INDEPENDENT	Self-directed; doing on one's own
PRODUCT	A product or output of some type is mentioned or included

(i.e., Quade's test). The student group's average pre-course GPA served as the covariate, or control variable, to take into account differential student performance across the semesters (Lawson, 1983; Quade, 1967;). Hedges' g was also calculated, another measure of effect size used when the sample size is small. IBM SPSS Statistics for Windows, Version 26.0 was used to carry out the statistical analyses (IBM Corp. Released 2019. Armonk, NY: IBM Corp.).

Coding and qualitative content-analysis of students' definitions of creativity

A coding scheme was developed to code the students' definitions of creativity (SQ1, Table 5), including the two-part definition of creativity used by many educators (i.e., novel and useful) and two additional themes identified from the student responses (i.e., independent and product) (Table 6). This survey question was content-analyzed independently by the two analysts, after which discussion took place until agreement regarding the final codes was reached. The first-time inter-rater reliability (IRR), a measure that indicates the level of initial agreement between two analysts who are coding data, for this coding scheme was Cohen's $\kappa = 0.73$ (Norusis, 2005), suggesting good agreement beyond chance. Given the same treatment (i.e., implementation of a design thinking methodology) and small class size (i.e., approximately 25 students per year), data from 2017 and 2018 were pooled for data analysis. We included only those students who provided both pre- and post-responses.

Quantitative analysis of students' individual creativity perspectives

For the pre- and post-survey statistical analysis corresponding to the question on individual beliefs about creativity, we included only those students who provided both pre- and post-responses. Statistical analysis was performed in IBM SPSS using the non-parametric version of a paired-samples *t* test (i.e., related samples Wilcoxon signed rank test), given the smaller sample sizes leading to uncertain normality. The effect size was also determined with Glass' delta, which is a measure of practical significance for pre vs. post measures (Lakens, 2013). All other Likert scale post-survey questions were compiled and analyzed in Microsoft Excel (Ver. 2019, Microsoft Corporation, Redmond, WA).

RESULTS

Student Groups' Enhanced Performance on Sustainable Design Challenges May be Associated with the Use of Design Thinking

Upon comparing the results of the projects before the use of design thinking (2016, n=7) versus with the use of design thinking (2017 and 2018, n=15), the 2017–2018 semesters had the higher average overall project scores (Table 7). This difference was statistically significant (p = 0.048)

Table 7. Comparison of the overall project score and each individual dimension score before (2016, n = 7) vs. with design thinking (2017–2018, n = 15). Statistical analysis was performed with non-parametric one-way ANCOVA (i.e., Quade's test) (*p ≤ 0.05).

Rubric dimension	Score without Design Thinking, 2016 (points) (±SD)	Score with Design Thinking, 2017–2018 (points) (±SD)	Effect size (Hedge's g)
Design thinking (1 point)	0.50 (± 0.17)	0.67 (± 0.17)*	1.14
Novelty (1 point)	0.58 (± 0.11)	0.67 (± 0.19)*	0.71
Usefulness (1 point)	0.76 (± 0.27)	0.81 (± 0.18)	0.43
Sustainability (1 point)	0.51 (± 0.17)	0.67 (± 0.13)*	1.15
Total project score (4 points)	**2.35 (± 0.61)**	**2.82 (± 0.53)***	**1.04**

when considering the overall project score as determined by all four dimensions. Additionally, the effect size was large, with Hedge's g = 1.04 (Lakens, 2013). This suggests that the use of a design thinking methodology may be associated with enhanced overall performance on these sustainability design solutions. The results of the projects corresponding to each individual dimension were also examined (Table 7). Again, the 2017–2018 semesters (with design thinking) had the higher average score for the design thinking, novelty, and sustainability dimensions, all of which were statistically significant (p = 0.024, p = 0.031, p = 0.038, respectively) with a large effect size (Hedge's g = 1.14, g = 0.71, g = 1.15, respectively). Scores on the usefulness dimension did not increase significantly (p = 0.695) and had a small effect size (Hedge's g = 0.43).

Students' Definitions of Creativity Remain the Same After Being Exposed to Design Thinking

Changes in how students define creativity were assessed by their pre- and post-survey responses. In defining creativity on the pre-survey during fall 2017 and fall 2018, 77% of the total respondents (n = 39) identified the concept of novelty, originality, or newness as part of their definitions while only 23% included usefulness (i.e., value, functionality, good solution) (Table 8). Twenty-three percent (23%) of respondents associated "independent thought or action" with creativity, and 15% mentioned

Table 8. Students' definitions of creativity from the pre- and post-survey for the combined 2017 and 2018 semesters (n = 39)

	Percentage of students including concept in their definition (%)	
Concept	**Pre-survey**	**Post-survey**
Novelty	77%	82%
Useful	23%	21%
Independent	23%	36%
Product	15%	8%

a product or output of some type as part of their definitions. Interestingly, on the post survey, the distribution of responses (n = 39) was approximately the same for the respondents when defining creativity – 82% identified novelty, 21% identified usefulness, 36% identified independent thought or action, and 8% mentioned a product or output in their definition. Thus, the students overwhelmingly associated creativity with novelty and to a much lesser extent usefulness.

Students' Perceptions of Their Individual Creativity Increase as a Result of This Course and Design Thinking

For fall 2017 and fall 2018, responses on both the pre- and post-survey corresponding to the question on individual beliefs about creativity were received from 39 students (74% of enrolled students). Approximately seventy-two percent (72%) of pre-survey respondents agreed or strongly agreed that a person could learn to be creative (Table 9). On the post-survey, this percentage rose slightly to 77%, suggesting a slight positive impact of the course on students' perceptions of their ability to learn to be creative. However, a related-samples Wilcoxon signed rank test showed a non-statistically significant difference between the pre- and post-survey responses (p = 0.46) and the effect size was small with Glass' delta = 0.12 (Lakens, 2013). When the data is disaggregated by gender, the percentage in each group (i.e., male and female) agreeing or strongly agreeing with this statement increased equally by 5%, although the males' pre-survey percentage was higher than that of the females. The impacts on creativity perception however were found to be different for each semester (Table 9). In 2017, the overall increase was significant (p = 0.038) with a medium effect size (Glass' delta = 0.43), attributed to the statistically significant increase (p = 0.038) and medium effect size (Glass' delta = 0.60) for the female students as they comprised the majority of the class. However, for all students in 2018, the percentage decreased slightly. Additional self-reported assessment results from the post-survey revealed that 57% of students thought their ability to function creatively as a result of this course increased or developed to a large or very large degree, and was observed to a greater extent in female students (Table 10).

Table 9. Percentage of students agreeing or strongly agreeing that a person can learn to be creative.

Combined 2017 and 2018 semesters					
Overall (n = 39)		**Male (n = 19)**		**Female (n = 20)**	
Pre	Post	Pre	Post	Pre	Post
72%	77%	79%	84%	65%	70%
p=0.46 (Wilcoxon) *Glass' delta = 0.12*		*p=0.79 (Wilcoxon)* *Glass' delta = –0.057*		*p=0.30 (Wilcoxon)* *Glass' delta = 0.29*	
Fall 2017					
Overall (n = 20)		**Male (n = 6)**		**Female (n = 14)**	
Pre	Post*	Pre	Post	Pre	Post*
65%	80%	83%	83%	57%	79%
p=0.038 (Wilcoxon) *Glass' delta = 0.43*		*no change*		*p=0.038 (Wilcoxon)* *Glass' delta = 0.60*	
Fall 2018					
Overall (n = 19)		**Male (n = 13)**		**Female (n = 6)**	
Pre	Post	Pre	Post	Pre	Post
79%	74%	77%	85%	83%	50%
p=0.37 (Wilcoxon) *Glass' delta = –0.21*		*p=0.79 (Wilcoxon)* *Glass' delta = –0.19*		*p=0.28 (Wilcoxon)* *Glass' delta = –0.51*	

*statistically significant at $p < 0.05$

Table 10. Students' perceptions of their individual creativity.

Rate the degree to which your ability to function creatively increased or developed as a result of this course.

Combined 2017 and 2018 semesters					
Overall (n = 44)		**Male (n = 22)**		**Female (n = 22)**	
Large to Very Large Degree	Very Small to Medium Degree	Large to Very Large Degree	Very Small to Medium Degree	Large to Very Large Degree	Very Small to Medium Degree
57%	43%	45%	55%	68%	32%
Fall 2017					
Overall (n = 24)		**Male (n = 9)**		**Female (n = 15)**	
Large to Very Large Degree	Very Small to Medium Degree	Large to Very Large Degree	Very Small to Medium Degree	Large to Very Large Degree	Very Small to Medium Degree
58%	42%	33%	67%	73%	27%
Fall 2018					
Overall (n = 20)		**Male (n = 13)**		**Female (n = 7)**	
Large to Very Large Degree	Very Small to Medium Degree	Large to Very Large Degree	Very Small to Medium Degree	Large to Very Large Degree	Very Small to Medium Degree
55%	45%	54%	46%	57%	43%

While the quantitative data is inconclusive, there is anecdotal evidence to suggest that the course had a positive impact on students. One student said the following on the post-survey, "*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.*" This statement shows the development of confidence in creative ability. Focus group participants were also asked to describe any changes in their perceived creativity resulting from the course. The following statements by focus group participants demonstrate the positive impact of this design thinking 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'."*
- *"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."*

Interestingly, design thinking was mentioned or discussed in over two-thirds (68%) of the individual statements made for this question in the focus group, including any of the design thinking stages (i.e. empathize, define, ideate, prototype, test or refine) listed individually or as a whole process. This qualitative assessment of students' perception of their creativity suggests that students associated design thinking with changes in their perceived creativity.

DISCUSSION

The relationship between design thinking and various measures of student performance are explored in this study, including students' product (*RQ1*) and individual creativity (*RQ2*), as well as their ability to apply sustainability practices to develop solutions to a group design challenge. For the evaluation of group design solutions in pursuit of *RQ1*, a series of rubrics were adapted from the literature to assess sustainability practices, product creativity, and use of design thinking in the students' semester design projects. This is the first time applying these rubrics, particularly Genco and Moss's treatment of creativity, to evaluate a product of a design thinking process. The analyses suggested that the products produced by student groups formally exposed to design thinking were more novel (a significant component of the definition of creativity), offered solutions that were more sustainable, and scored higher overall (Table 7), indicating that exposing students to design thinking increased the creativity of group solutions to their sustainability design challenge (*RQ1*). Increased performance in the area of design thinking was expected given the integration of a formal instructional process. The statistically significant increase in the novelty of the solutions is exciting and is likely not a result of just one step of design thinking (e.g., ideation) as other studies suggest (Chulvi et al., 2012; Daly et al., 2012), but as a result of the engaging in the entire process and developing new mindsets. Teaching students to re-imagine the user experience, understand user needs, and frame the problem first-hand through fieldwork may increase creative production, as usefulness is also an important dimension of creativity, and testing and receiving user feedback can also help students to converge on more creative solutions. The nature of design thinking itself, being experimentation-based and encouraging students to think without judgment nor have a fear of failure, also likely contributed to the increase in the novelty of the solutions as students developed a mindset where they saw failure as a growing opportunity and ambiguity as a chance to be more creative. The concomitant statistically significant increase in the sustainability and creativity dimensions of the project suggests that the combination of sustainability and design thinking is a viable approach for students to develop socially- and environmentally-responsive solutions to complex problems. Overall, the idea that design thinking may be associated with enhanced product creativity on sustainability project solutions is consistent with the idea that creativity is indeed a skill that can be developed (Candy, 2013; Chiu & Salustri 2010; Epstein et al., 2008; Hewet, 2005; Stenger, 2018). Ongoing data collection in future semesters as well as implementation of our study approach in design thinking classes taught by other instructors will enable more definitive conclusions to be drawn regarding the association of design thinking methodologies with product creativity and sustainability.

To capture individual student changes in creativity in pursuit of *RQ2*, we evaluated how their perspectives of creativity changed as a result of this design thinking course through questions on the pre- and post-surveys and during focus groups. A notable percentage (57%) of students assessed their development related to creativity highly as a result of the course (Table 10), particularly true for female students. Individual student statements on the survey and focus group corroborate the positive impact of the course on their perceived creativity, demonstrating the development of creative confidence and increase in their creative capacity, and many attribute this increase specifically to the incorporation of design thinking into the curriculum, thus suggesting that exposure to design thinking influenced students' individual perspectives of their own creativity (*RQ2*). Design thinking may also have a greater impact on female students because it is strongly related to elements of human-centrality and social design. Quantitatively, there was also an increase from the start to the end of the course in students' individual beliefs that they could learn to be creative (Table 9) suggesting a slight positive impact from the course, although this was not found to be statistically significant. These impacts however were different for each semester. This difference could be due to the different gender distributions in these two years (60% female in 2017 and 30% in 2018), with possible negative domination or influence of the majority gender on the minority group's perceptions, engagement, and confidence. The combination of working in a setting having numerical male dominance (a numerical majority of male colleagues that leaves the females outnumbered) and working in the technical sector (where women are negatively stereotyped) predict the highest levels of experienced gender identity threat, particularly among women who highly identify with their gender group, which in turn negatively predicts their work engagement and career confidence (van Veelen, Derks, & Endedijk, 2019). Stereotype threat has also been suggested as an explanation for gender differences in performance on math tests (i.e., when female test takers are reminded of negative female stereotypes, they perform worse compared to males) (Boucher, Rydell, & Murphy, 2015; Spencer, Steele, & Quinn, 1999). The prominence of gender and the associated stereotypes can be extrapolated to data collected in our study where females may see themselves as having lesser creative ability in a class dominated by males. Ongoing research will provide additional data needed to further investigate this question.

Further in pursuit of *RQ2*, students' definitions of creativity were also analyzed and were found not to change after taking the course. Students associated novelty with creativity, but not usefulness, which is surprising given how much designing for user needs is emphasized in the course and in an inherently creative design thinking process. The lack of student association between usefulness and creativity may align with the fact that there was no significant increase in the usefulness dimension on the project after being exposed to design thinking. Yet, the usefulness dimension of the project scores has the highest magnitude compared to the other dimensions measured, suggesting that students are thinking about the usefulness of their solution but are not consciously linking the concept with creativity. Since students' creative output, performance, and perceived confidence increased, students' definitions of creativity may not actually be representative of enhanced creativity, and therefore may not a good assessment tool for looking at creativity. This aligns with Atman et al. (2008)'s work which showed that knowledge of the design process does not drive performance, albeit in their work students' design knowledge did not translate to application of that knowledge (Atman, Kilgore, & McKenna, 2008), whereas within this study, the opposite trend emerges (i.e., students performed creatively, but failed to define creativity in its complete form).

We acknowledge several limitations to the current study and data interpretation. First, the data is collected from one course at one institution. The sample size is small and restricted by the number of students enrolling in *Design for the Environment*. The class is capped at thirty students to allow use of certain learning spaces and to support implementation of certain in-class activities. This small sample size suggests that the quantitative results around the association of design thinking with product creativity and sustainable engineering practices are tentative and larger, well-controlled studies (with a proper control group) in classrooms by other instructors at institutions offering design thinking classes are needed to build on these efforts and enable more definitive conclusions to be drawn regarding these associations.

There are also some limitations to using surveys and focus groups to obtain responses from students. As with any method of self-reporting, there could be potential differences between thoughts or actions that actually occurred versus those described during the surveys and/or focus group discussion. Ideas could have been omitted because of lack of detail or precision in writing and speaking, issues with recollection, or specific to the focus groups, discomfort speaking in front of other students. In addition, social desirability biases could have led to student responses that were enhanced to include thoughts that may not have actually been internalized or else primed by the responses of other students.

One factor that we cannot control as we compare 2016 (before design thinking) with 2017–2018 (with design thinking) is the change in the level of instructor effectiveness. It is natural for an instructor to improve with the same course over time. The instructor's Office of Measurement and Evaluation of Teaching (OMET) overall teaching effectiveness score rose from 4.13 in 2016 to the average of 4.66 in 2017–2018 on a 5-point scale. Additionally, each semester, there is variability in students' pre-existing knowledge of sustainability and design thinking. Some students are exposed to sustainable engineering concepts if they have taken other sustainability-focused courses and to design thinking in the one other general engineering course offered at the same university. These prior experiences will influence our study measures and students' pre-existing knowledge in sustainability and design thinking are not currently captured.

Finally, the fact that students work in groups on different project topics could introduce bias given the differing project characteristics and potential differences in possibilities for creative solution development. However, the way groups are formed ensures that each member of the group has a high level of interest in the project topic. One approach to addressing these limitations is to compare groups working on the same challenge. While there are multiple challenges with two groups dedicated to developing solutions and some challenges appear across years, the sample size of these project subgroups is too small at this time to analyze separately. Further, despite evaluating the projects randomly to mitigate bias, it is possible that the instructor and teaching assistant were not completely blinded to the year of the project and class version (design thinking or no design thinking) if they recalled which projects were produced in which year and class version, suggesting the potential for some researcher bias to be present in the evaluations.

CONCLUSIONS

Creative and sustainable thinking are critical to innovation in the engineering industry. Educators can support students' development of these vital skills by providing a platform for them to exercise and receive feedback on the various aspects of creativity. In this work, we focused on enhancing the cognitive aspects of creativity by integrating a design thinking methodology into our course. Using a combination of literature-informed assessment methods (performance-based and self-reported measures) over three semesters, our results suggest that long-term immersion in design thinking may be associated with positive and/or significant outcomes related to student creativity. This is an exciting finding because it provides empirical evidence showing an association that was previously undocumented. Specifically, we found that student groups exposed to design thinking had significantly higher design project scores across the novelty, sustainability, and design thinking dimensions, suggesting that design thinking enhances the quality of solutions to complex engineering and sustainability challenges. Students' beliefs in their creative capacity also increased as a result of incorporating design thinking into the curriculum. Students became more confident about their ability to be creative as a result of this course and the unique characteristics of design thinking, measured through both individual student statements in the focus group and their survey responses. Our findings importantly contribute to supporting the call for the use of design thinking methodologies for large societal and environmental challenges, underscore its importance in promoting students' problem-solving skills in the 21st century, and further, help shrink the current gap in the creativity and design thinking literature.

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DISCLOSURE

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REFERENCES

"An introduction to design thinking process guide." n.d. *Hasso Plattner Institute of Design at Stanford.*

Adams, J. P., Kaczmarczyk, S., Picton, P., & Demian, P. 2007. "Improving problem solving and encouraging creativity in engineering undergraduates." *International Conference on Engineering Education.*

Amabile, T. M. 1982. "Social psychology of creativity: A consensual assessment technique." *Journal of Personality and Social Psychology*, 43(5): 997–1013.

Atman, C. J., Adams, R. S., Cardella, M. E., Turns, J., Mosborg, S., & Saleem, J. 2007. "Engineering design processes: A comparison of students and expert practitioners." *Journal of Engineering Education*, 96(4): 359–379.

Atman, C. J., Kilgore, D., & McKenna, A. 2008. "Characterizing design learning: A mixed-methods study of engineering designers' use of language." *Journal of Engineering Education*, 97(3): 309–326.

Badke-Schaub, P., Roozenburg, N., & Cardoso, C. 2010. "Design thinking: A paradigm on its way from dilution to meaninglessness?" Proceedings of the 8th Design Thinking Research Symposium (DTRSB) Interpreting Design Thinking, Sydney, 19–20 October, 39–49.

Bandura, A. 1997. "Self-efficacy: The exercise of control." New York, NY: W.H. Freeman.

Benson, L. C., Becker, K., Cooper, M. M., Griffin, O. H., & Smith, K. A. 2010. "Engineering education: Departments, degrees and directions." *International Journal of Engineering Education*, 26(5): 1042–1048.

Boucher, K. L., Rydell, R. J., & Murphy, M. C. 2015. "Forecasting the experience of stereotype threat for others." *Journal of Experimental Social Psychology*, 58: 56–62.

Brown, T., & Wyatt, J. 2010. "Design thinking for social innovation." *Stanford Social Innovation Review,* 31–35.

Candy, L. 2013. "Evaluating creativity." In *Creativity and Rationale: Enhancing Human Experience by Design*, edited by J.M. Carroll, 57–84. New York: Springer.

Carter, C. 2016. "Let's stop talking about THE design process." *Medium*. https://medium.com/stanford-d-school/lets-stop-talking-about-the-design-process-7446e52c13e8

Charyton, C., Jagacinski, R. J., Merrill, J. A., Clifton, W., & DeDios, S. 2011. "Assessing creativity specific to engineering with the revised creative engineering design assessment." *Journal of Engineering Education*, 100(4): 778–799.

Charyton, C., & Merrill, J. A. 2009. "Assessing general creativity and creative engineering design in first year engineering students." *Journal of Engineering Education*, 98(2): 145–156.

Chiu, I., & Salustri, F. A. 2010. "Evaluating design project creativity in engineering design courses." *Proceedings of the 1st Canadian Engineering Education Association Conference, Queen's University Kingston, Ontario.*

Chulvi, V., Mulet, E., Chakrabarti, A., López-Mesa, B., & González-Cruz, C. 2012. "Comparison of the degree of creativity in the design outcomes using different design methods." *Journal of Engineering Design*, *23*(4): 241–269.

Clark, R., Stabryla, L., & Gilbertson, L. 2018. "Use of active learning and the design thinking process to drive creative sustainable design solutions." *Proceedings of ASEE Annual Conference and Exposition*, *Salt Lake City, UT.*

"Criteria for accrediting engineering programs, 2020–2021." 30 Nov. 2019. *ABET*. May 19, 2020. p. 4. https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2020-2021/

Cropley, D. H. 2015. "Promoting creativity and innovation in engineering education." *Psychology of Aesthetics, Creativity and the Arts,* 9(2): 161–171.

Cropley, D. H. and Cropley A. J. 2000. "Fostering creativity in engineering undergraduates." *High Ability Studies*, 11(2): 207–219.

Daly, S., Mosyjowski, E., & Seifert, C. 2014. "Teaching creativity in engineering courses." *Journal of Engineering Education*, 103(3): 417–449.

Daly, S. R., Yilmaz, S., Christian, J. L., Seifert, C. M., & Gonzalez, R. 2012. "Design heuristics in engineering concept generation." *Journal of Engineering Education*, 101(4): 601–629.

Dam, R.F. & Siang, T.Y. 2021. "5 stages in the design thinking process." Interaction Design Foundation, December 23, 2021. https://www.interaction-design.org/literature/article/5-stages-in-the-design-thinking-process

"Design thinking bootleg." 2021. *Hasso Plattner Institute of Design at Stanford,* December 23, 2021. https://dschool.stanford.edu/resources/design-thinking-bootleg

"Design thinking defined." n.d. *IDEO*, December 23, 2021. https://designthinking.ideo.com/

de Vere, I. 2009. "Developing creative engineers: A design approach to engineering education." *International Conference on Engineering and Product Design Education, Brighton, UK.*

Doppelt, Y. 2009. "Assessing creative thinking in design-based learning." *International Journal of Technology and Design Education*, 19: 55–65.

Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D., & Leifer, L. J. 2005. "Engineering design thinking, teaching, and learning." *Journal of Engineering Education*, 94(1): 103–120.

Epstein, R., Schmidt, S., & Warfel, R. 2008. "Measuring and training creativity competencies: Validation of a new test." *Creativity Research Journal*, 20(1): 7–12.

Felder, R. M. 1988. "Creativity in engineering education." *Chemical Engineering Education*, 22(3): 120–125.

Felder, R. M. 2012. "Engineering education: A tale of two paradigms." In *Shaking the Foundations of Geo-engineering Education,* edited by B. McCabe, M. Pantazidou, & D. Phillips, 9–14. Leiden: CRC Press.

"4Ps of creativity: What are they?" 2016. *SparcIt,* May 22, 2020. https://medium.com/sparcit-blog/4ps-of-creativity-what-are-they-8e639423f5a1

Genco, N., Hölttä-Otto, K., & Seepersad, C. 2012. "An experimental investigation of the innovation capabilities of undergraduate engineering students." *Journal of Engineering Education*, 101(1): 60–81.

"Get started with design thinking." 2021. *Hasso Plattner Institute of Design at Stanford,* December 23, 2021. https://dschool.stanford.edu/resources/getting-started-with-design-thinking

Guilford, J. P. 1950. "Creativity." *American Psychologist, 5*(9): 444–454.

Hewet, T., Czerwinski, M., Terry, M., Nunamaker, J., Candy, L., Kules, B., & Sylvan, E. 2005. "Creativity support tool evaluation methods and metrics." *National Science Foundation Workshop,* 10–24. http://www.cs.umd.edu/hcil/CST/Papers/creativitybook_final.pdf

"History." n.d. *IDEO,* May 19, 2020. https://designthinking.ideo.com/history

"How do people define design thinking?" n.d. *IDEO*, December 23, 2021. https://designthinking.ideo.com/faq/how-do-people-define-design-thinking

Huntzinger, D. N., Hutchins, M. J., Gierke, J. S., & Sutherland, J. W. 2007. "Enabling sustainable thinking in undergraduate engineering education." *International Journal of Engineering Education*, 23(2): 218–230.

Kelley, D. 2020. "Creative confidence map." *Hasso Plattner Institute of Design at Stanford University*, May 19, 2020. https://dschool.stanford.edu/resources/david-kelleys-rules-of-creative-confidence

Korsunskiy, E., Hoffman, K., Gormon, G., Angst, W., & Roeschmann, C. n.d. "Toward a peer-powered resource teaching human-centered design projects at the university level." *The University of Texas at Austin,* December 22, 2019. https://designcreativetech.utexas.edu/toward-peer-powered-resource-teaching-human-centered-design-projects-university-level

Lakens, D. 2013. "Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs." *Frontiers in Psychology,* 4: 1–12.

Lawson, A. 1983. "Rank analysis of covariance: alternative approaches." *The Statistician*, 32(3): 331–337.

Luenendonk, M. 2015. "Idea generation: Divergent vs. convergent thinking." *Cleverism*, May 22, 2020. https://www.cleverism.com/idea-generation-divergent-vs-convergent-thinking/

Mahboub, K. C., Portillo, M. B., Liu, Y., & Chandraratna, S. 2004. "Measuring and enhancing creativity." *European Journal of Engineering Education*, 29(3): 429–436.

Moore, L. 2018. "Teaching and Learning Studio Faculty Workshop." *Hasso Plattner Institute of Design at Stanford,* May 19, 2020. https://dschool.stanford.edu/events/teaching-learning-studio-jan18

Moss Jr, J. 1966. "Measuring creative abilities in junior high school industrial arts." Washington, DC: *American Council on Industrial Arts Teacher Education*.

Nagel, R., Pierrakos, O., & Nagel, J. 2013. "A versatile guide and rubric to scaffold and assess engineering design projects." *Proceedings of the American Society for Engineering Education Annual Conference & Exposition, Atlanta, Georgia*.

Norusis, M. 2005. *SPSS 14.0 Statistical Procedures Companion*. Upper Saddle River, NJ: Prentice Hall, 152, 183.

Quade, D. 1967. "Rank analysis of covariance." *Journal of the American Statistical Association*, 62(320): 1187–1200.

Razzouk, R., & Shute, V. 2012. "What is design thinking and why is it important?" *Review of Educational Research*, 82(3): 330–348.

Rhodes, M. 1961. "An analysis of creativity." *The Phi Delta Kappan*, 42: 305–310.

Royalty, A., Oishi, L., & Roth, B. 2014. "Acting with creative confidence: developing a creative agency assessment tool." In *Design Thinking Research, edited by* H. Plattner, C. Meinel, & L. Leifer*,* 79–96. Switzerland: Springer International

Sarkar, P., & Chakrabarti, A. 2011. "Assessing design creativity." *Design Studies*, 32(4): 348–383.

Schell, J. n.d. "Design thinking has a pedagogy problem…and a way forward." *The University of Texas at Austin,* December 22, 2019. https://designcreativetech.utexas.edu/design-thinking-has-pedagogy-problem-way-forward

"Shape the future with design thinking." n.d. *Hasso-Plattner-Institut*. December 23, 2021. https://hpi.de/en/school-of-design-thinking/design-thinking.html

Spencer, S. J., Steele, C. M., & Quinn, D. M. 1999. "Stereotype threat and women's math performance." *Journal of Experimental Social Psychology*, 35: 4–28.

Stenger, M. 2018. "Can we learn to be more creative?" *informED,* June 18, 2018. https://www.opencolleges.edu.au/informed/features/can-learn-creative

Sternberg, R. J. 2012. "The assessment of creativity: An investment-based approach." *Creativity Research Journal*, 24(1): 3–12.

Taurasi, E. M. 2007. "Forging a path for today's engineers." *Design News,* 62(11): 62–66.

Thoring, K., & Müller, R. M. 2011. "Understanding the creative mechanisms of design thinking: an evolutionary approach." In Proceedings of the Second Conference on Creativity and Innovation in Design, 137–147.

Torrance, E. P. 1979. "An instructional model for enhancing incubation". *The Journal of Creative Behavior*, 13(1): 23–35.

"United Nations Sustainable Development Goals." n.d. *UN*, December 22, 2019. https://sustainabledevelopment.un.org/sdgs

van Veelen, R., Derks, B., & Endedijk, M. D. 2019. "Double trouble: How being outnumbered and negatively stereotyped threatens career outcomes of women in STEM." *Frontiers in Psychology*, 10:150.

Watson, M., Barrella, E., Wall, T., Noyes, C., & Rodgers, M. 2017. "A rubric to analyze student abilities to engage in sustainable design." *Advances in Engineering Education*, 6(2).

"What is design thinking?" n.d. *Hasso-Plattner-Institut.* December 23, 2021. https://hpi.de/en/school-of-design-thinking/design-thinking/what-is-design-thinking.html

Zampetakis, L. A., Tsironis, L., & Moustakis, V. 2007. "Creativity development in engineering education: The case of mind mapping." *Journal of Management Development*, 26(4): 370–380.

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