Developing reflective engineers through an arts-incorporated graduate course: A curriculum inquiry

Abstract

Engineering curricula have traditionally focused on preparing students to become specialized individuals with technical knowledge, while devoting less attention to reflective thinking about real-world engineering practice, which is fraught with complex, unpredictable, and ambiguous problems that require broader skills. More recently, engineering educators have recognized the need to broaden the engineering curriculum, in part by incorporating the arts and humanities. The present study involves the development of an arts-integrated graduate course in environmental engineering. The purpose of this paper is twofold: first, to explore how engineering students have experienced this new curriculum; and second, to understand how it has enhanced their reflective thinking skills. We employed a descriptive, intrinsic case study approach using student interviews, writing assignments, and artwork collected from the course as our primary sources of data. The findings show that there is clear potential for the arts to provide meaningful changes in engineering students' learning to become reflective thinkers. Hence, we suggest that engineering education be re-imagined by making the arts an essential part of the engineering curriculum to develop reflective engineers who are willing and able to navigate the "swampy lowlands" of engineering practice. The course provides a model for incorporating the arts to foster reflective thinking in graduate engineering education and the study contributes to the literature a distinctive, qualitative evaluation of its potential impacts.

Key words: curriculum; engineering education, arts-based curriculum, reflective thinking, graduate education

Introduction

Every discipline where teaching and learning take place has a curriculum. At one level a curriculum consists of the lessons, activities, and assessments as described in the course syllabus. The students' experiences of the curriculum are also important. The work of curriculum scholars, then, does not and should not remain within the field of education. One of their roles is to introduce relevant curriculum theory to other fields, such as engineering, to help provide a more meaningful and educative experience for students (Dewey, 1915/2001). One such curriculum theory that can be beneficial to engineering is that of Eisner, whose work is grounded in Dewey. Eisner was a major advocate for the role of the arts in reimagining different kinds of education (Eisner, 2005). In this paper, we analyze and present multiple ways in which engineering graduate students experienced the art-based components of a multidisciplinary curriculum designed to foster reflection in engineering.

Habits and skill of reflection are of interest because engineering curricula have traditionally focused on preparing students to become specialized individuals who possess primarily technical knowledge while coming short of helping them understand the complexities, ambiguities, and uncertainties of engineering practice that exist in real life situations. Schön (1983) problematized overreliance on technical rationality in educating engineers and other professionals, where detached, objective, standardized, and nomothetic knowledge is highly valued. Schön wrote, "in the varied topography of professional practice, there is a high, hard ground where practitioners can make effective use of research-based theory and technique, and there is a swampy lowland where situations are confusing 'messes' incapable of technical solution" (p. 42). According to Schön, engineers are typically trained to walk on the high, hard ground rather than the swampy lowland. As a result, engineering education, grounded in such positivistic ideals, has likely produced "the craftsman who knows how to do a job well but produces nothing essentially new" (Eisner, 2005, p. 79), while what is needed is a reflective engineer who is willing and able to navigate complex engineering problems that are full of uncertainties and ambiguities. Hence, Schön proposed that reflective practice accompany the traditional epistemology of technical rationality as an integral component of engineering education.

Bucciarelli and Kuhn (1997) have also noted the mismatch between engineering education and engineering practice:

> Engineering education now excels at preparing students as specialized individuals for work in a particular slot within an object world set in a well-defined organizational hierarchy. Students possess quite sophisticated knowledge of instrumental methods and scientific principles when they leave school, but are severely constrained in their ability to apply their knowledge because they have not experimented with it or tested its limits. (p. 219)

Bucciarelli and Kuhn attributed shortcomings in engineering education to several factors, including: courses "are typically taught in authoritarian ways", "[c]ritical reflection … is, if not openly discouraged by faculty, ultimately devalued by the student as a waste of time and energy" (p. 214), and "there is rarely any serious attention given to the nature of the student experience" (p. 217).

In the decades that have passed since Schön and Bucciarelli and Kuhn have pointed out these shortcomings, our experience has been that the education of engineers has changed very little in this regard in most disciplines. However, researchers continue to recognize the need to better educate engineers to address ill-structured, "wicked" problems (see Jonassen et al., 2006; Seager et al, 2012, Lönngren, 2019, 2017) and the topic of reflection, broadly defined, seems to be "on an upward trend" in engineering education research (see Sepp et al., 2015 and Author et al., 2019), due in part to the work of the Consortium to Promote Reflection in Engineering Education (CPREE, see www.cpree.uw.edu).

Engineering students trained today will be working in a world that is rapidly changing, is becoming increasingly complex, and is being built not only on technology but on globalization and inter-connectedness. Kamp (2020) suggests founding "educational change on the things technology cannot do, the things that are strictly human!", and advises that "Engineering students have to learn that people policies, environmental aspects, politics, economics or cultural values often override disciplinary expertise" (p. 17). The idea of building engineering curricula with attention to globalization, social and cultural factors, humanitarianism, and social justice, though not new to some engineering educators, may also be on the rise. Attempts to broaden engineering curricula have included creating learning communities consisting of faculty from engineering and disciplines in the humanities and developing new courses that integrate liberal arts with engineering (e.g., Li et al., 2016). Course objectives in liberal arts-infused courses have focused on such concepts as critical thinking, reflection, and identity development (e.g., Wood & Martello, 2020). In considering how to re-engineer the engineering education system, the National Academy of Engineering (2005) proposed that:

> learning disciplinary technical subjects to the exclusion of a selection of humanities, economics, political science, language, and/or interdisciplinary technical subjects is not in the best interest of producing engineers able to communicate with the public, able to engage in a global engineering marketplace, or trained to be lifelong learners. (p. 52)

In the present project, an interdisciplinary team of scholars from curriculum studies, engineering education, studio art, civil/environmental engineering, and cognitive psychology designed and implemented a course curriculum with an objective to develop reflective engineers. More specifically, we attempted to find out whether the integration of the arts into engineering would improve engineering students' reflective thinking. This was an experimental curriculum with "the idea of the laboratory" (Dewey, 1915/2001, p. 64) where there was no pre-defined outcome in terms of its impact on the students. As Dewey noted, it was "only by trying that such things can be found out" (p. 64) through experimentation in the region of the unknown.

The general aim of this arts-integrated curriculum[1] was to help engineering students to become reflective thinkers who develop the habit of critical, creative, and imaginative thinking about broader social, human, environmental, and ethical contexts when discussing problems and making decisions in their engineering practice. The purpose of this paper, then, is twofold: first, to explore how engineering students have experienced the curriculum; and second, to understand in what ways it has enhanced (or not) their reflective thinking.

In the next four subsections we present converging areas of scholarship that provide a logical basis for the present curriculum: the developmental role of art in education, the centrality of reflection in learning, the incorporation of the arts and humanities in engineering education, and a summary of extant research on reflective thinking.

The Role of Art in Education[2]

Influenced by Dewey (1934/1980), who held the view that art is a particular quality of human experience, Eisner was a strong proponent of integrating art into education and the school curriculum. Like Dewey, Eisner believed that art is not something to be placed on a pedestal;

---

[1] In this paper, we use the terms arts-incorporated, arts-integrated, and arts-based interchangeably. We also use the term curriculum in reference to our course because it is designed to serve as a model for adaptation into other courses and potentially across the entire engineering curriculum.

[2] We refer to education in a broad sense here. For example, we all (the authors) are involved with education in different fields.

rather, it is a living process of human experience. He believed in the role of the arts in promoting cognitive activities that make unique forms of meaning possible. Eisner (2005) states that the work of art is "a source of surprises, a discovery, a form that embodies a conception not held at the outset" (p. 79). It fosters the skills and dispositions such as invention, imagination, sensitive perception, insight, and judgment, which are of central importance in any student's learning.

However, Eisner and Powell (2002) lamented how universities were negligent of integrating art into the curriculum and suggested how the vision of schooling and teaching may change if art was made an essential part of education. They state:

> Currently, our schools and universities teach with a limited view of cognition, one that is often positivistic, goal-driven, and outcome-oriented… We value the right answer, quick solutions, and close-ended systems of meaning wherein students have to aspire to predetermined standards. But if we take other forms of cognition seriously, such as the forms present in artistry, our vision of schooling and teaching might change. (p. 154)

To further argue for the advancement of art-integrated forms of cognition, Eisner (2002a, 2002b) explains how art can afford opportunities to transform brains (i.e., biological resources) into minds (i.e., forms of cultural achievement). He writes, "Minds come into existence as individuals secure varied forms of experience in the course of their lives and, through those forms of experience, learn to think" (Eisner, 2002b, p. 341). Hence, the development of the kinds of minds we want to nourish depends on the learning opportunities that the school provides. For Eisner (2005), schools, including universities, must provide the conditions that enable students to discover deep and diverse forms of meaning in their lives by incorporating the arts into the curriculum. Therefore, the arts are "not mere diversions from the important business of education; they are essential resources" (p. 84).

The Centrality of Reflection in Learning

Uncritical thinking comes from the lack of reflection, which leads one to accept things at their face value. To avoid it, we must reflect, thus be engaged in "reflective thinking" (Dewey, 1910, p. 13). Through reflective thinking, we doubt, question, and challenge what is happening and what is experienced, seeking additional evidence, new data, in order to understand the situation and develop better ideas. Hence, for Dewey, reflective thinking means "judgment suspended during further inquiry" (p. 13), which involves willingness to endure a condition of mental uneasiness, such as doubt, perplexity, or confusion. It is a good mental habit that needs to be practiced in real life, as Dewey (1910) maintains, "We do not learn from experience. We learn from reflecting on experience" (p. 78). We must reflect on experience and engage in reflective practice in order to improve our daily practice.

Schön (1987) makes a claim that some skilled technicians may lack reflective practice: they have limited ability to make good decisions, for they lack consideration for the consequences of their actions. Bolton and Delderfield (2018), too, assert that reflective practitioners take their share of responsibility for not only their own actions and values, but also for the broader contexts involving the political, social, and cultural situations within which they live, learn, and work. The educative process for developing reflective practitioners is not to be merely aimed at responding to given questions and providing prescribed answers; rather, it should help them develop their own search for questions, while not minding the process that may produce uncertainty, unrest, and conflict.

How, then, can we involve such an educative process in the engineering classroom where the habit of reflective thinking and reflective practice can be developed? We once again get inspiration from Eisner (2004), who states that involvement in the arts can afford artists judgement in the absence of rule. As such, the arts incorporated in engineering education can teach engineering students how to act and judge by having them develop the habit of reflective thinking and reflective practice. Moreover, the arts can teach students not to be rigidly attached to predefined aims but to capture the opportunity when the possibility of better aims emerges—which is referred to as "the exploitation of surprise" and the opening of oneself to "the uncertain" (Eisner, 2004, p. 6). The arts-incorporated engineering curriculum, therefore, may help engineering students be engaged with the reflective practice in which they question their professional knowledge from different perspectives in order to make wise, informed decisions.

Reflective Practice and an Arts-Infused Engineering Curriculum

The idea to integrate the arts into engineering education is not new and efforts to do so are renewed from time to time, such as in response to the ABET Engineering Criteria 2000 (see e.g., Ollis et al. 2004), via the STEAM movement to integrate "A"—Arts—into existing programs of STEM (Science, Technology, Engineering, and Mathematics) (see Colucci-Gray et al., 2019), and via a recent call for higher education to integrate the arts and humanities with science, engineering, and medicine (NASEM, 2018).

Sochacka et al. (2016) considered the potential benefits of bringing educators and students together from across STEAM disciplines, particularly, engineering and the visual arts. They suggested that teaching creativity through the integration of engineering with arts would require changes in the manner of teaching, from being authoritative (c.f. Bucciarelli and Kuhn, 1997, p. 214) to being facilitative, which could encourage students to take a more holistic approach to solving problems in ways that incorporate the engineer's beliefs, values, and relationship to the problem at hand (Sochacka et al., 2016, p. 33). They advocated a process of "reflecting on the self while possessing an awareness of the self in interaction with others, all while envisioning new possibilities for our social world" (p. 21).

Shuster (2008) has argued that exposure of engineering students to liberal and fine arts made them better members of society and better engineers. If engineers focused their attention solely on solving quantitative problems in their discipline, Shuster suggests that they lose “suppleness” in their thinking. The true world of engineering “is cloaked in ambiguity and doubt” (p. 97), and the way to help students learn how to deal with that ambiguity is through the liberal and fine arts.

Anderson et al. (2009) described a campus-wide initiative labeled *Creative Campus* to foster creativity across all disciplines, including engineering. The researchers described four collaborative ventures in which engineering faculty and students worked side-by-side with peers in theatre, dance, telecommunications, film, and music. Anecdotally, the researchers reported that engineering students came away from these experiences with mutual respect for the passion, dedication, and talent of students in the paired disciplines. Another example is found at Olin College, which institutionalized the idea of cross-disciplinary collaborations. The goal of the Olin curriculum was to break disciplinary boundaries in order to promote student thinking in non-traditional ways. The college does not have traditional academic departments. Instead, faculty function as a single interdisciplinary group (Kerns, et al., 2005). The curriculum includes Arts (creativity, innovation, design, communication) as a key dimension, and engineering students are encouraged to express and apply their creativity.

Findley and Mirth (2016) who studied the connections between the arts and engineering reported the outcomes of a liberal arts course intended to appeal to engineering students. Their course assignments included writing projects which encouraged the students to think about the relationship between the arts and engineering regarding the meanings and uses of form and function. Their analysis of student writing indicated an overall increase in student ability to create new ideas and an improved ability to see value creation in engineering design. Findley and

Mirth encouraged more appreciation among students in technical disciplines of the impact of the arts on the world around them. Cantero et al. (2015) introduced art and creativity in engineering graphics education and researched the impact of a workshop carried out in a course on engineering graphics at a university in Spain. In the workshop, the students generated different three-dimensional modelling solutions from pictorial works of art by American artist Frank Stella. Cantero et al. found that the workshop, dubbed Stella 3D, helped the students improve their capacity to generate new ideas and spatial skills, which supports the idea that engineering students' creativity can be motivated through an art-related learning activity.

Generally, engineering is seeing more and more integration of various aspects of the arts into its education in multiple creative ways (see also Dixon et al., 2017; Li & Cheng, 2018; Marshall, 2013; Robinson et al., 2015). A common thread among arts-integrated curricula has been an interdisciplinary orientation of engineering education whereby the arts are an integral part of the curriculum.

Research on Reflective Thinking

As indicated previously on page 5, one of the purposes of this work is to understand ways in which our curriculum has enhanced (or not) the reflective thinking of students. Here we briefly summarize existing literature on the topic of reflective thinking, which has been largely quantitative (i.e., statistical) in nature and directed at lower grade levels rather than graduate-level engineering education.

For example, Fwu et al. (2018) compiled a Likert-type survey to examine the interplay of culture, reflective thinking, and academic persistence in tenth-grade high school students. Akpur (2020) also compiled a Liker-type survey to study structural relationship patterns between reflective thinking, critical thinking, creative thinking, and academic achievement in students attending university preparatory classes. Sánchez-Martía, et al. (2018) studied reflective thinking via a Likert-type survey conducted after an intervention involving narrative writing by second-year college students majoring in education, while Farahian, Avarzamanib, and Rajabic (2020) used a Likert-type survey and quantitative coding/analysis of student writing and interview responses to examine the effects of portfolio writing on the reflective thinking of second-year university students of unreported majors in an EFL (English as a Foreign Language) course. Finally, Afshar and Rahimi (2016) used two Likert-type surveys and quantitative coding/analysis of interview responses to examine relationships between reflective thinking, emotional intelligence, and foreign-language speaking ability in third- and fourth-year English language majors.

In the field of engineering education "reflective thinking" as such has not yet received much empirical attention but there have been efforts to explore reflection more broadly. At the primary school level, Wendell, Wright, and Paugh (2017) used naturalistic inquiry to study reflective decision-making in the engineering design work of elementary school students. At the undergraduate level, student perceptions of a variety of reflection activities have been explored using (a) a Likert-type survey with graphical methods of statistical analysis (Turns et al., 2017) and (b) narrative methods with semi-structured interviews (Roldan et al., 2019). Finally, at the graduate student level, Svyantek et al. (2015) used a mixed-methods approach to examine the impact of electronic portfolios (ePortfolios) on graduate student identities as they reflect on their roles of research, teaching, service, and lifelong learning in preparation as future faculty members. This paper thus adds to the literature on reflective thinking a qualitative/interpretive perspective with a focus on graduate engineering education.

The Curriculum and its Implementation

What is distinctive about the curriculum described here is that it links the arts with developing reflective thinking and reflective practice, as well as creativity and critical thinking (see Author et al., 2017; Author et al., 2019). The general aim is to enable engineering students to become reflective thinkers who develop habits of critical, creative, and imaginative thinking about the broader social, environmental, and ethical context. The curriculum was collaboratively developed by several co-authors of this paper: an education professor who specializes in curriculum studies and narrative inquiry, an engineering professor who specializes in chemical and environmental engineering, an experimental psychology professor who specializes in cognition and cognitive neuroscience, and a postdoctoral researcher and instructor who specializes in engineering education research.

After a one-credit pilot course in spring 2017, we implemented a full 3-credit, arts-integrated graduate course two years later, which is the focus of this paper. The course was offered as an elective through the civil and environmental engineering department open to all students with gradate standing. Students learned of the course through their advisors and word of mouth from students who took the pilot course previously. The course met weekly, with each session lasting for about three hours, and was led by two of the co-authors: the postdoctoral researcher/instructor and the engineering professor. A variety of other people were also involved as guest speakers, including the other three faculty co-authors, each of whom led a unit of several weeks' duration for the course. Additional guest speakers included a colleague from the museum, a professor from civil/environmental engineering, and two Ph.D. Candidates who worked with the experimental psychology professor.

The course thus involved a variety of activities, three of which are the focus of this paper. The first activity was *Autobiographical Writing*, which consisted of a pair of assignments asking each student to write narrative essays about themselves and create an optional piece of companion artwork. These were completed early and late in the semester to document the students' growth and referred to below as prologue and epilogue, respectively. The second activity was *Engineering Meets Art* in, which a studio art faculty member (a co-author of this paper) provided an opportunity for art students and engineering students to collaborate for five weeks on an art-making project. The third activity was *Visual Thinking Strategies* (VTS), a pedagogical technique that uses visual art to foster students' skills of observation and communication. VTS is a student-centered facilitation method to foster inclusive group discussion through art (see http://vtshome.org/about/). VTS has been used in medical education (Reilly et al., 2005) and has great potential for use in other disciplines like engineering (Hailey et al., 2015). Yenawine and Miller (2014) gave a thorough description of the VTS protocol[3] and explained how art-based class discussion supports critical thinking in not only the arts and humanities but also the sciences.

Other class activities included guest speakers (e.g., on topics relating engineering to art and the environment, narrative and communication), group discussions about potential ethical dilemmas, reading/discussing a novel with a strong environmental justice theme, and weekly essay writing that was either prompted/focused or open-ended reflections on the week's topic and/or activity. For this paper, which aims to explore the role of the arts in developing reflection, we purposefully focus on students' learning outcomes that resulted from the three activities discussed above.

---

[3] VTS has three specific and carefully worded questions: 1) What's going on in this picture; 2) What do you see that makes you say that; 3) What more can you find? Please see Yenawine and Miller (2014) for more information about VTS.

Research Methods and Data Sources

We present our research as an intrinsic case study (Stake, 1995) in which the case of one instantiation of the [removed for blind review] curriculum is discussed as a way to explore how the curriculum enhanced the students' reflective thinking to be more accepting of the ambiguities and uncertainties that are present in engineering practice. We utilized a case study by drawing on Stake's notion that "[a] case study is expected to catch the complexity of a single case" (p. xi), through which we sought to highlight what can be learned about and possibly applied to other cases. The research question for this study was: How might the arts and humanities as used in this offering of the [removed for blind review] course help engineers become more reflective thinkers who have greater awareness of and sensitivity to the broader contexts of societal well-being and sustainability?

With this question, we sought to get an "in-depth understanding" (Schwandt & Gates, 2018, p. 343) of the students' experiences of the [removed for blind review] course, based on the data from a variety of sources (Brown, 2008; Merriam, 1998). Conducting this intrinsic case study, our first obligation was not to build theory or to generalize it to other cases, but to understand the particularity and complexity (Schwandt & Gates, 2018; Stake, 1995) of the [removed for blind review] graduate course provided in Spring 2019. Although we hoped to present readers with "good raw material for their own generalizing" (Stake, 1995, p. 102), we believe that our conclusions and insights are of wider relevance in terms of reflective thinking practice through the incorporation of arts in engineering education.

Nine graduate students were enrolled in this offering of the course, with majors in civil, environmental, and chemical engineering at the master's and doctoral levels, making a diverse group of four men and five women. This group had a significantly higher number of women than the engineering-wide enrollment averages at both our university (25% in 2020) and nationally (28% in 2019, ASEE 2020), but only slightly more than the enrollment averages for the sub-discipline of environmental engineering at our university (50% in 2020) and nationally (47% in 2019, ASEE 2021). Also consistent with institutional and national enrollment averages, over half the participants were international students while the rest were from the United States. These nine students volunteered to participate in the study, and the only criterion for inclusion in the study was enrollment in the [removed for blind review] course. All students received course credit applicable to their degrees for completing the course, and they were offered modest monetary incentives for participating in the two optional interviews. Pseudonyms have been assigned to each participant and used in the Findings and Discussion below.

We collected the data for the study from three main sources: interviews, nonparticipant classroom observation, and course assignments. Upon receiving approval from our Institutional Review Board, we interviewed each student once early in the semester (pre-interview) and again shortly after the course had ended (post-interview). Both of the interviews were semi-structured, conducted face-to-face and one-on-one, and audio recorded. The pre-interview asked the students about their backgrounds, their thoughts on reflection (e.g., What do you think reflection is?), the role of the arts in engineering (e.g., What do you think about the relationship between the arts and engineering?), and their images of an engineer (e.g., What kind of engineer do you want to become?). The post-interview was intended to explore whether there was any change in students' understanding of reflection after taking the course. Hence, many of the same questions were asked again during the post-interview. See the appendix for the lists of questions prepared for these interviews.

We thus conducted a total of 18 interviews with each interview lasting 40 minutes to an hour. The interviews were transcribed by one of the authors and crosschecked by another author, neither of whom were the primary course instructors. Every class was observed by these same two researchers, who took field notes for triangulation of the data from the interviews. The third data source came from two course assignments involving student autobiographical writing and their art products. The autobiographical writing consisted of a prologue and an epilogue. The prologue was the student narrative written at the beginning of the semester wherein they were encouraged to reflect on who they are, how they have become who they are, how they have chosen an engineering path, and other aspects of their life which they believe are important in shaping who they are or are becoming. The epilogue was a documentation of the student personal growth, if any, at the end of the semester. For the epilogue, the students were encouraged to create some artwork to accompany their narratives. Suggestions for the student artwork ranged from a variety of forms, such as drawing, painting, poetry (along with its performance), craft, crochet, collage, sculpture, drama performance, or whatever artistic medium they wanted to use. Finally, students were asked to present their epilogues with the art works they had produced.

The art products that resulted from the *Engineering Meets Art* activity were also used as data sources for the study. In this activity, engineering students were grouped with graduate students from the School of Art to collaborate on an art project. Two class periods bookended this five-week activity, and students met outside of class time to complete the work. In general, the engineering students took the lead on finding engineering concepts or topics for the art and on writing artists' statements, while the art students led the design and creation of the artwork illustrating the concept(s).

Data Analysis

We mainly used sequential analysis that requires the researcher "to strictly follow the text to analyze its development from the beginning to the end" (Flick, 2014, p. 374). Since we had a prologue and epilogue assignment, in addition to a pre-interview and a post-interview for each student, it was critical that we analyzed the pre-interview, prologue, post-interview and epilogue in a sequential manner in order to observe if there was any change from the beginning to the end of the semester. The purpose of this sequence was to ensure that we "refrain from using later parts of the text for understanding earlier parts" (p. 374).

After transcribing the interview data, we used a qualitative content analysis method by reading and rereading each interview transcript carefully several times (Elo et al., 2014). The purpose was to reconnect with each participant's narratives as closely as possible. The content analysis process was applied to all of our data sources both inductively and deductively (Elo et al., 2014). We first started with an inductive approach without *a priori* categories. That is, we coded the data verbatim, honoring the interviewee's voice (Saldana, 2013) while identifying the themes emerging from the voice of the interview. Then, we used a deductive approach to coding the data, which corresponded to the identified categories or objectives of the interviews—that is, the impact of the curriculum as a whole, the impact of art-making, and the impact of VTS on each student's reflective thinking development. The categories and themes were then compared with those derived from the inductive approach, across the participants' interview transcripts as well as writing assignments, to enable the final set of categories and themes. These processes were conducted between the first two authors for constant peer review (Morse, 2018).

Findings

Overall, the students had a positive experience with the course even though they were initially skeptical about its artful methods and potential benefits at the beginning of the semester. For example, a majority of the students said that they did not feel comfortable with the idea of being in a class where the arts were the main medium of the class activities. But they later realized how the arts helped them develop reflective thinking, particularly through such course activities as the *Autobiographical Writing* assignments, the *Engineering Meets Art* collaboration, and the *Visual Thinking Strategies* exercises. Overcoming initial feelings of hesitation and confusion because they were "not into art" (Aston, pre-interview), the students warmed up to the course and said that they benefitted from it and would certainly recommend it. The following statement captures some of these sentiments:

> I'll recommend the course. I see a lot of people who hardly reflect upon themselves, so maybe they'll get more reflective to take this course. I think it's important for them [because] many people don't realize how important the art of reflection is, how you should be reflective. I think people really lack that. (Sinclair, post-interview)

The reason for the students' overall satisfaction with the course came from their realization of the multiple benefits of the arts-related activities in which they participated.

Below, we will discuss our findings in more detail, organized using three categories: 1) Impacts of the curriculum as a whole; 2) Impacts of art-making; and 3) Impacts of Visual Thinking Strategies. The first category has three themes: a) A deeper understanding of reflection and reflective thinking; b) Learning to embrace ambiguities and uncertainties in engineering; and c) Realizing the need for reflection. The second category has two themes: a) Paying attention to social issues; b) Moving from being "not into art" to realizing the value of the arts. The third category has two themes: a) Becoming more reflective; and b) Appreciating multiple perspectives. See Table 1 for a summary of the findings with corresponding data sources.

Table 1. Emerging themes and associated data sources

Themes	Data sources reflecting themes		
	Interviews (pre- / post-)	Autobiographical Writing	Artwork
Impacts of the curriculum as a whole			
a) A deeper understanding of reflection and reflective thinking	Aston, Haylee, Hyana, Michele, Sinclair, Vikki	Haylee, Michele, Vikki	Haylee, Vikki
b) Learning to embrace ambiguities and uncertainties in engineering	Sinclair	Alice, Sinclair, Thomas	Haylee, Hyana
c) Realizing the need for reflection	Haylee, Sinclair, Thomas, Vikki		Haylee, Hyana
Impacts of art-making			
a) Paying attention to social issues			Haylee, Hyana, Ryder, Sinclair, Thomas, Vikki
b) From being "not into art" to realizing the value of the arts	Alice, Aston, Haylee, Hyana, Sinclair, Thomas, Vikki	Haylee, Hyana	
Impacts of VTS			
a) Becoming more reflective	All	Vikki	
b) Appreciating multiple perspectives	Haylee, Hyana, Vikki	Thomas	

Impacts of the Curriculum as a Whole

a) A deeper understanding of reflection and reflective thinking

The students showed a deeper understanding of reflection by the end of the semester. While they started the course with a simple notion of reflective thinking as "overthinking" (Haylee, Michele, Vikki, pre-interviews), they later related reflection to the development of the self, particularly the development of their professional and personal behaviors. After the course, some came to realize that doing reflection means “thinking deeply, [and not] accepting things that others say too easily” (Haylee, post-interview). Others considered reflecting as “matching between your heart, [what you practice,] and your passion” (Aston, post-interview). Still others defined reflection as “[thinking back with a] more open mind” (Hyana, post-interview) and with “more calmness” (Michele, post-interview).

The students also discussed how the class helped them reflect more on their future self. Michele, for instance, stated that “[the class] helped me in the reflection I was required to do for figuring out what I truly wanted for my future” (Michele, epilogue). Also, Vikki wrote:

> [this class] taught me useful life skills. [It] really helped me enhance my thinking capabilities, and not just my engineering knowledge. I developed different areas of my brain that I haven’t really utilized in college or the engineering field, like my inner artsy and creative side that is hidden away. I even practiced utilizing my newly developed creative expressive skills by working with a team to create a collaborative art piece and creating my own companion art piece for this final project. (Vikki, epilogue)

Vikki acknowledged how the course taught her to realize her inner artistic and creative side, and implied how this creativity may be useful in her engineering practice. Similarly, Haylee wrote of the changes in her perception of her capabilities of reflexivity, creativity, and responsibility: “Reflexivity, creativity, and responsibility are some of the changes I can find in myself. I also learned to ask more questions and don’t accept the facts perfunctorily. […] I found artwork not only relaxing but an encouragement to grow” (Haylee, epilogue).

b) Learning to embrace ambiguities and uncertainties in engineering

Most students pointed out that the course helped them embrace their discomfort in dealing with uncertainties, complexities, and differences. For example, Sinclair wrote, “This semester, I’ve kind of sorted myself out and I no longer search for clarity. I've decided to exist calmly within uncertainties and [paradoxes]" (Sinclair, epilogue). Additionally, Alice's prologue and epilogue clearly show how her binary (right-or-wrong) thinking has changed. Here is an excerpt from Alice's prologue:

> From a young age I felt that decisions and actions were simple and the 'right' course of action could be determined if the situation was thought about rationally. I believed that things were right or wrong and there was very little middle ground. … My tendency to favor decisions that were black and white, right or wrong continued during my schooling. … I was able to excel in my undergraduate classes because I was comfortable that each question only had one right answer and if I paid attention and studied, I could get the answer on tests. … I dislike science classes often due to the lab portion of the class because the experimental results are always variable and while variability can be reduced it cannot be eliminated. The variability always made me uncomfortable when drawing conclusions to experiments. I was always especially displeased when the results I was supposed to get in a standard lab experiment did not occur. (Alice, prologue)

But then, Alice's epilogue below shows a deeper reflection of how engineering problems cannot be solved by only technical knowledge but need to be combined with "a story behind it," i.e., "the complete narrative of a problem" requires a holistic view of engineering:

> This class and this semester taught me that every problem statement has a story behind it, a story that [the work of] environmental engineers likely involves a community in some way. Learning this story can help me learn what happened at a site that caused it to be contaminated or what challenges are presented by a drinking water supply and the community that relies on the water… In this way truly understanding the complete narrative of a problem is the only way to find an appropriate solution. (Alice, epilogue)

These narratives of Alice's (which echo a guest-speaker-led activity described in Authors et al., 2020) indicate how the class helped her unlearn her belief that there is little middle ground between right and wrong. She used to feel uncomfortable to get varied results in her experiments. Her willingness to "learn this story" requires much reflection on what else is going on with a particular situation rather than just the technical problems.

Similarly, Thomas wrote of his awareness of the "swampy lowlands" of engineering, and how real-life problems are ill defined, complex, and not simple:

> The hundreds of hours I have spent in classrooms learning engineering had undoubtedly got me used to thinking of a world in which everything is solvable with mathematics, physics, and chemistry. [The] class was a healthy detour in my education path because it took me down off the cloud I was [on] and made me see that real-life situations are complex, not well defined, and they require more than science to be solved. I think the main thing I gained from this class was that it opened my eyes to the "swampy lowlands" where many of the problems we are going to deal with exist. … I wish technical knowledge were everything I have to take care of, but the reality is not that simple. I am happy I have started to feel more comfortable with the uncertainty and complexity of our world. (Thomas, epilogue)

Thomas realized that technical knowledge is not everything he needs to have to solve an engineering problem. Sinclair echoes the sentiment that Thomas exhibited:

> I think that one thing that I learned from this course is that I used to think engineering is simple and just pretty straightforward, like you plug in the inputs and you get some outputs. …The more you dig deep into a particular subject, it gets trickier and more hypothetical than factual. It's simple only up to a certain extent, and as you go further down, it gets more complex than what it appears to be. (Sinclair, post-interview)

It is clear that both Thomas and Sinclair have become more open to complex and unknown problems. Engineering is not a simple matter of "plugging in the inputs" and get outputs.

c) Realizing the need for reflection in engineering

Thus, the students realized that engineering does not constitute only technical and objective knowledge, with which they used to believe engineers can solve real-life problems. Rather, they began to understand that the deeper they dig into a particular engineering subject, the more complex, "trickier," and more abstract it may get. This realization shows that the students see the need to be more reflective and more thoughtful, as Vikki stated:

> I think it [the course] has definitely influenced the engineer I want to become and why I'm doing what I'm doing, who I'm serving, think about all the implications, all the considerations, like whether they'll be cultural or environmental. […] you don't really think about like whenever you get your engineering degree, you kind of come out like machines, the calculators, who just do the equations, make a design. I think the course really made you become more reflective, more thoughtful. (Vikki, post-interview)

Vikki noted how she thought engineers were like "machines" and "calculators" who "just do the equations" but they have to be "more reflective and more thoughtful." She continued:

> I think that for engineers to learn about environmental justice, sources of policies, is important because they can see how solutions in engineering affect everyone, how they can disproportionately affect some. Sometimes the loudest people are the top of economic class because they have the most resources and means to voice their concerns, and the bottom class of people can get left behind. (Vikki, post-interview)

The narrative above shows the student's greater awareness of broader social issues such as environmental (in)justice, policies, and unequal access to resources.

Another student, Haylee, reflected on how the course has changed her into a more open-minded person, and more connected to the community and society:

> [The course has changed] us from narrow-minded to open-minded persons. Because we always focus on our calculations, on professional things that we learned from the university, and will be disconnected from the community and society and their feeling and behaving. So, I think it helps us to be more connected with our surroundings. It helps us to think more broadly. (Haylee, post-interview)

Thus, both Vikki and Haylee reflected on the role of engineers in influencing their surroundings and the need to be connected to the community and society.

Impacts of Art-making

a) Paying attention to social issues through art-making

For the *Engineering Meets Art* activity, a faculty member from the School of Art was invited as a guest speaker and kicked off a 5-week collaborative print-making project between the [our] students and her own art students. Nine engineering students and eight art students were put into groups of three or four to collaborate on developing ideas for art making and creating the artwork. In particular, the art students took the lead on art making while the engineering students led the writing of the artist statements.

Below, we present some of their art productions and artist statements[4] that indicate their reflective thinking.

[4] Both art productions and artist statements were done in groups.

Figure 1

Group 1's artwork and artist statement: At the mercy of mercury

At the Mercy of Mercury

[…] *Another goal that this group pursued was to show the toxicity of mercury in the environment. Mercury is one of the most toxic metals that can enter the atmosphere and water and contaminates the environment. The primary anthropogenic sources of mercury are fossil fuel combustion, coal burning, mining and other chemicals production industries.* […] *The colors played the most important roles in our artworks. In the first category of our arts the color brown and dirty green and blue used to show contamination, the rough borders also created a toxic looking print. Moreover, the shapes of fishes and factories used to show how the profit-making activities of humans endanger the lives of creatures.* […] *In summary, art is a common language that all people can understand, and we can share our beliefs, concepts and messages in a simple, impressive and more tangible way using art. That's why we reflected on mercury contamination, formed a narrative and depicted our story using art methods.*

Group 1 put a lot of reflection into this project (Figure 1). To illuminate contamination in the set of prints shown here, they used the color brown and dirty greens and blues; and they made the borders rough to symbolize a toxic environment. In addition, they included images of a factory and fish to indicate how profit-making activities of humans endanger the lives of all creatures. They clearly reflected on the presence and impacts of environmental damage caused by humans to convey their beliefs, concepts and messages through an art from.

Figure 2

Group 2's artwork and artist statement: The fifth leg of the cat

<u>*The Fifth Leg of the Cat*</u>

Creating an edition of screen prints[,] our group collaborated by creating a composition connecting environmental engineering and graphic design to emphasize how extinction of species is tied to climate change resulting from air pollutants.

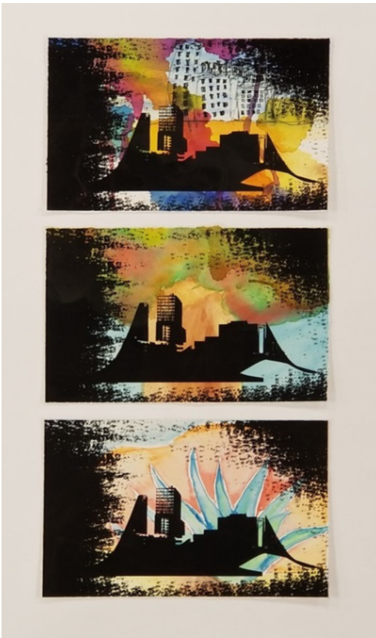
Graphically incorporating the image of an extinct thylacine or Tasmanian Tiger layered into other imagery associated with the environment[,] our design serves as a poster to linking the fields of art and engineering to raise awareness through social commentary.

> […] *Due to climate change, we are currently in the Holocene extinction[, where] the current rate of extinction of species is estimated to be 100-1000 times higher than the natural background rate. The last recorded living thylacine died out in 1935 as the result of hunting and loss of natural habitat due to the growing logging industry in Tasmania.*

Group 2 reflected on the links of species extinction to climate change resulting from air pollution (Figure 2). As they incorporated the image of an extinct species (a Tasmanian tiger) overlaid with an engineering drawing (related to the Gaussian plume rise equation), they raised awareness of the detrimental impacts of climate change caused by human activities such as logging and hunting. Thus, they too clearly reflected on the presence and impacts of environmental damage caused by humans and used art to communicate it.

Figure 3

Group 3 students' artwork and artist statement: BEElieve



BEElieve

The concept of today's troubles can have one believe that they are sectionalized. Engineers attempt to solve engineering problems, politicians attempt to solve political problems, and artists attempt to bring around social change. While every field can start a movement, it takes all three together to make a movement that stands the test of time.

The bee population, throughout the world, has been dying at staggering rates over the past decade. Engineers have attempted to solve the problem by designing synthetic pollinizers, yet synthetic methods do not match what mother nature has created. Politicians have attempted to solve the problem by increasing regulation of harmful pesticides, yet the bee population continues to be in decline. Artists have attempted to solve the problem by bringing around social change and awareness, yet the world does not seem to take them seriously. The art in front of you is the combination of all three (Engineers, Politicians, and Artists) coming together to conceptualize the problem fully. The series of art includes equations for 3-D modeling [of] the propagation of pesticides responsible for the death of thousands of pollinators. The buildings in the middle of each frame are the curvature of this model and depict how society continues this process of spreading this poison. Finally, the watercolor backdrops are the image of a world untouched by humanity and therefore safe for pollinators.

The artwork of Group 3 (Figure 3) reflects how each field cannot work independently to solve a social problem; it takes collaboration among different fields. They argue that engineers, politicians, and artists should get together to solve the problem of the disappearing bee population and its serious impacts on human life. These images are the results of the students' reflection on the social problem created by harmful pesticides and the artist statement emphasizes how interdisciplinary teamwork is needed to conceptualize social problems and create an environment that is humane and safe for bees and other pollinators.

b) Moving from being "not into art" to realizing the value of the arts

As mentioned earlier, about half of the students did not show much interest in the artful aspect of the course at the beginning of the semester because they were "not into art" and thus expressed some concerns over the expectation of creating artwork (Alice, Aston, Thomas, Vikki, pre-interviews; Thomas, Vikki, epilogue). By the end of the course, however, the students had a better understanding of the role of the arts in engineering. They believed that the arts could help them become better engineers and better communicators. Some students even realized that there is a similarity between engineering and the arts.

The interviews show how some students were initially mistaken about the course. For example, Vikki lamented about how she was reluctant to participate in the *Engineering Meets Art* activity: "I came in very hesitant especially when y'all said we're gonna be making art and do these things, I was like, 'Oh my gosh.' It was very shocking at first and very scary" (Vikki, pre-interview). But, by the end of the course, she became more appreciative of the value of the arts:

> So I guess that with the arts and humanities, you think more creatively, you practice that side of your brain which usually we don't practice and so I imagine like one big side of the brain one small side and so when you're working out both sides I think you just have better solutions and better things to offer as an engineer. (Vikki, post-interview)

Vikki realized the value of the arts incorporated into engineering, which is to allow engineering students to think more creatively without "sticking to the script," and help them become better engineers:

> I think, when you incorporate arts classes into engineering, it allows you to be more creative or think outside the box. It's less how do we address this problem and more how you do it. I think it's right brain, your more creative side, and it really strengthens that. So, I think you're able to come up with more creative solutions, more outside-the-box thinking, rather than stick to the script. I think not every problem has a certain solution; you have to think outside the box. And so, when you practice and exercise that right brain, it makes you a better engineer overall because you have more creative ideas. (Vikki, post-interview)

Similarly, in his pre-interview, Thomas shared a reservation about the course he had after the first few class meetings: "[…] when I saw the assignments, I felt like I don't want this class. And actually, I wanted to drop […] the class" (Thomas, pre-interview). But interestingly it was this student who suggested we continue the art collaboration activity in later courses, as he said, "The art collaboration was something that I enjoyed a lot. I would like that you [instructors] keep doing this" (Thomas, post-interview).

Aston was also among those who were "not into art" (Aston, pre-interview), but he gradually learned to appreciate the value of arts-related activities:

> I am, to be honest, I'm not into art anyway, and whenever I look at some pictures I kind of didn't bother to get the meaning of that. But now, from the class, from the examples from the videos, and some meanings [brought by] the artists from [the] art school, I can tell that now I'm in a better position to […] try to understand the meaning of their work. I do not […] look at it with impatience now […]. (Aston, post-interview)

Aston became more receptive to perspectives different from his own and willing to try to understand without judgement: “So the most important thing I found is how you can keep your mind open with different thought processes. You have to keep your mind open, accept all different thoughts without being judgmental” (Aston, post-interview).

Alice and Haylee learned that the arts could help engineers communicate more effectively with other people who are not in the engineering field. Haylee saw art as a powerful language for effective communication: “Art is a powerful language with which we can communicate with people effectively. I could convey the goal of my research with a simple artwork but in an attractive way” (Haylee, epilogue). Similarly, Alice said, “I know I have a hard time communicating engineering things in a way that other people can understand, so I think that arts and humanities could really help with that” (Alice, post-interview). For Alice, art could facilitate effective communication because “I think maybe taking a step back and looking at it [in a] more abstract kind of art way helps me realize the connections between things I didn't see before” (Alice, post-interview).

Hyana found similarities between engineering and the arts:

> During the processes when we are doing the project, I realize that art is like engineering. Besides idea[s], knowledge, accuracy, and repetition are essential for art expression. Art is not something merely romantic, or good-looking, or looks awesome; it contains practice and accumulation of experience where we know less. Arts, in this way, shares the similarity with engineer[ing]. I should try to understand people not majoring in engineering, just as how we understand art as engineers. (Hyana, epilogue)

Hyana then saw connections between the arts and engineering profession: “[Arts] and humanities can help engineers have more dimensions and enjoying life which has positive impact on their career” (Hyana, post-interview).

Hyana's perception of the relation of the arts and engineering also reverberated in Sinclair's experience of the arts-related activities: "I think art can influence engineering work. I think if you are really artistic as an individual, it will help you in any professional field because art help[s] you to introspect more than you usually do" (Sinclair, post-interview).

Impacts of Visual Thinking Strategies

Finally, we will discuss the impacts of Visual Thinking Strategies (VTS), which was used as a pedagogical technique that involved viewing and discussing pieces of visual art. We took the students to the museum to learn and practice VTS together with trained facilitators (a museum staff member and one of the course instructors). Then, each student took turns in small groups leading VTS sessions in the museum galleries. We later provided the students with more VTS practice in the classroom with photos related to both visual art and science/engineering.

a) Becoming more reflective

All the students in the study agreed that the VTS practice was one of the most interesting aspects of the course, and evidence of this was found in all post-interviews and epilogue essays. They said that VTS helped them most in becoming reflective because they had to listen to other people rather than focusing on what they were thinking (Michele, post-interview) while learning to "keep their mind open and accept all different thoughts" (Aston, post-interview).

Most important to the goal of the course, the students realized the benefits of the VTS practice to their reflective thinking development. Vikki wrote,

> [After] we learned how to practice VTS in the museum, I felt my critical and reflective thinking skills grow. This new way of thinking can be applied widely to all sorts of applications, not just art. The method really allowed me to practice critical and reflective thinking. (Vikki, epilogue)

As this example shows, the students recognized that reflective thinking can be developed by listening to others, keeping their minds open, and accepting all different perspectives. As they discussed artwork through the VTS method, they also envisioned how the skills could be applied to a wide variety of other situations.

b) Appreciating multiple perspectives

Hyana appreciated VTS for teaching her to understand various perspectives. She stated, "[Only] after the VTS [did I realize that] even among the same group of engineers, [the perspectives] can vary so much. So, it's like I really need to be patient and to ask more questions to try to understand" (Hyana, post-interview).

Similarly, Haylee learned to appreciate multiple perspectives and take advantage of the differences: "VTS practice taught me that all persons think differently from each other, so we are not allowed to judge, we're not allowed to criticize, we should actually consider that people think differently and we should take advantage of these differences" (Haylee, post-interview).

Thomas's comment below could be considered a summary for the students' appreciation of the value of VTS:

> From the VTS experience, I learned that you could appreciate art as long as you pay attention to details, use your imagination, and remain curious about the intention of the artist. Besides learning VTS techniques to have a better experience when we encounter art, I want to focus on the implications in my professional life. As engineers and scientists, we try to find solutions to complex problems. It is in this situation that I see two qualities that can be learned from VTS. The first one is the ability to pay attention to small details and bring them to the bigger picture. The second one is the competence to listen carefully to others because we can learn a lot from different points of view. (Thomas, epilogue)

Thomas succinctly pointed out that VTS helped him be more appreciative of art, pay attention to details, and remain curious about the artist's work. He also explained how VTS could help engineers and scientists to pay attention to details while helping them see the bigger picture, and listen to others more carefully.

Discussions and Conclusion

The purpose of this article was to explore how engineering students experienced a course/model-curriculum that incorporated the arts, and to understand how it enhanced engineering students' reflective thinking. More specifically, we wanted to address the question: How might the arts and humanities help engineers become more reflective thinkers who have greater awareness of and sensitivity to the broader contexts of societal well-being and sustainability? Based on the analyses of a variety of data focusing on three major course activities (*Autobiographical Writing* assignments, *Engineering Meets Art* group projects, and *Visual Thinking Strategies* exercises), we have presented three dimensions of our findings: impacts of the [removed for blind review] curriculum as a whole, impacts of art-making, and impacts of VTS.

The findings show that the arts, incorporated into a course for engineers, can improve, promote, and foster students' reflective thinking. The students themselves were the ones who noticed the changes in their thinking resulting from the activities of art-making and Visual Thinking Strategies (VTS). They also realized how their improved reflective thinking skills could be transferred to their future engineering practice. These findings prompt us to reimagine the engineering curriculum, taking artistic forms of understanding more seriously.

Based on this, we will make two recommendations: (1) promote the arts as reflective practice in the engineering curriculum and (2) reimagine the engineering curriculum through the arts. These are further described in the sub-sections below.

Promote the Arts as Reflective Practice in the Engineering Curriculum

We first recommend that the arts be used more intentionally in the engineering curriculum to promote reflective practice. Contemporary German philosopher Bertram (2019) takes art as daily human practice, as he states, “art is exemplary of human practice as a whole” (p. 11), which enriches human practice in an “awe-inspiring manner” (p. 11). This means that art is not independent of other human practices such as mental, emotional, and intellectual capacities; rather, it is inevitably intertwined. To argue that “art is a reflective practice” (p. 78), Bertram theorizes the notion of reflection from two different perspectives: theoretical and practical. He observes that reflection has predominantly been understood in a theoretical manner in which reflection is used to objectify the object of reflection. In this theoretical attempt at understanding reflection, there is an epistemological gap between the knower and the known, posing a problem of relevance to one’s own practice.

An alternative to this problematic theoretical understanding of reflection, according to Bertram (2019), is practical understanding of reflection, understood as “an act of relating to oneself, which gives definition to other practices” (p. 88). In this act of relating to oneself, the distance between the knower and the known is removed as it relates to a practice influencing other practices as well as future practices. Hence, this practical sense of reflection can be empowered by art, as art helps us reflect human practices embedded in the world in a practical manner. Bertram states, “Art thus shows itself to be a specific kind of reflective practice” (p. 145), since reflective practice is understood as taking responsibility for one’s own personal and professional actions, assumptions, and feelings, and as being willing to stay with uncertainty, unpredictability and doubt (Bolton & Delderfield, 2018; Dewey, 1910).

As shown in our findings, engineering students educated with learning activities incorporating the arts can develop both reflective thinking and a specific kind of reflective practice in which reflection leads to something different. As they realized the need for reflection in engineering because they are not "machines" or "calculators" who just do the equations without reflection, the students in this study changed their understanding of reflection, which was previously understood from a theoretical perspective. The students first understood reflection as merely "overthinking," but later, as they experienced the arts-integrated curriculum, they were able to have a more practical understanding of reflection, relating it to the development of the self, paying attention to the development of their professional and personal behaviors.

As we learned from one of the students, art-based reflection has become a specific kind of practice where there is a "matching between your heart and practices and your passion, so [that] all kinds of things will be merged together in a work, in the process of reflection" (Aston, post-interview). This kind of reflective practice also lets students embrace ambiguities and uncertainties lurking around the work of engineering, by understanding that there is always "a story" behind an engineering issue which needs to be reflected upon. Accordingly, such practical understanding of reflection can lead to "more empowered reflection" (Bertram, 2019, p. 88) when it is fostered through artful methods in classroom. This also aligns well with the need to better educate engineers to address ill-structured, "wicked" problems that has been recognized by others in engineering education, such as Jonassen et al. (2006), Seager et al. (2012), and Lönngren (2019, 2017).

Reimagine the Engineering Curriculum with the Power of the Arts

Next, we want to encourage engineering educators to reimagine their curriculum and find ways to incorporate the arts in it. Sochacka et al. (2016) have provided insightful reflections on their experience with integrating art and engineering, and we hope this practice will become more common as others engage in similar experimentation. Engineering students are too often taught based on a curriculum heavily saturated with technical knowledge and tasks that demand following rules and formulas with predictable outcomes. The students in this study would likely agree with Eisner that "The arts teach a different lesson. They celebrate imagination, multiple perspectives, and the importance of personal interpretation" (Eisner, 2005, p. 132).

The findings presented in this paper show how the arts are important to the education and development of engineers. The students in this study have seen the power of the arts to trigger their creativity, critical thinking, and reflection, which enables them to think outside of the box for different solutions to a problem. The arts helped them realize their own possibilities which they would not have realized otherwise.

In conclusion, the arts have the power to provide meaningful changes in engineering students' learning to become reflective thinkers. Universities can no longer ignore integrating the arts into the curriculum. We need to change our vision of engineering education by making the arts an essential part of the curriculum. As Eisner (2005) notes, we "cannot in good conscience omit the [fine] arts" (p. 83).

It is also clear how art and reflection go hand in hand, making art a reflective practice as Bertram (2019) argues. In developing reflective engineers, the arts can be an important vehicle to make that happen. The arts can help and empower students to reflect as an act of relating to themselves, upon their practices as students and as future engineers, who choose to walk in Schön's swampy lowlands where much work of importance needs to be done.

Limitations and Future Research

We acknowledge here some limitations of the study due to the case context and the scope of the study. First, we are well aware of possible criticisms regarding the issue of generalizability because of the small number of subjects being investigated. This is a valid criticism when one translates qualitative research into quantitative language (Morse, 2018). However, our primary intention was to focus on the particularity rather than the generalizability of this course offering. Additionally, we have conducted other studies to add more perspectives to and/or widen the scope of the case study. In Morse's (2018) words, we seek to deliberately add "hard data" (p. 809) to our data mix to increase perceptions of rigor for some readers.

For example, in Author et al. (2018), we employed both qualitative analyses of writing samples ("soft data") and statistical analyses of survey responses ("hard data") to explore how the [removed for blind review] course affected the reflective thinking of another group of graduate students, and in Author et al. (2020), we examined quantitative pre/post survey data from the same group of students as in this paper. While the terms "hard" and "soft" may inadvertently function to devalue qualitative and promote quantitative research, we should point out that they have different strengths and weaknesses, and can be used to complement each other (e.g., see Creswell & Plano-Clark, 2017 and Green, Camilli, & Elmore, 2006). Future work will involve higher level interpretations of these various data sources.

Second, this study is limited in its considerable reliance on participants' self-report data (i.e., interviews and autographical writing). While the students' reflective thinking seems to have improved over the semester evidenced in the data, the actual impacts of their reflective thinking as engineers when they enter the engineering workforce are not clear. Longitudinal research may be needed to follow the engineering graduates in their professions in order to investigate how they exercise reflective thinking in navigating real complex engineering problems.

In this work, we focused on the experiences of engineering students in an arts-incorporated curriculum; however, another potential area for future research is to explore how students in the arts and humanities might benefit from collaboration with engineering students. Such an approach was taken by Guyotte et al. (2015), who explored what students in art and art education might learn from collaborating with students in STEM. Anecdotally, our experience with collaborative artmaking among groups of graduate students from environmental engineering and studio art seemed quite consistent with those of Guyotte et al. (2015) with respect to the challenges and benefits of collaboration, opportunities for which art students are rarely exposed due the individualistic nature of their programs. When setting up such a collaboration, care should be taken to ensure workloads are distributed and benefits are gained equitably by everyone involved.

Acknowledgements

[people and funding, removed for blind review]

Declaration of Interest

None

References

Afshar, H. S., & Rahimi, M. (2016). Reflective thinking, emotional intelligence, and speaking ability of EFL learners: Is there a relation? *Thinking Skills and Creativity, 19*, 97–111. https://doi.org/10.1016/j.tsc.2015.10.005

Akpur, U. (2020). Critical, reflective, creative thinking and their reflections on academic achievement. *Thinking Skills and Creativity, 37*, Article 100683. https://doi.org/10.1016/j.tsc.2020.100683

American Society for Engineering Education (ASEE) (2021). *Engineering Data Management System (EDMS)*. (2021, February 27). [Data set]. ASEE. https://survey.asee.org/

American Society for Engineering Education (ASEE) (2020). Engineering and Engineering Technology by the Numbers 2019. Washington, DC. (Revised January 11, 2021). https://ira.asee.org/wp-content/uploads/2021/02/Engineering-by-the-Numbers-FINAL-2021.pdf

Anderson, M., Todd, B., Burkett, S., Warren, G., Brown, M., & Cordes, D. (2009). Engineering collaborations with liberal arts. *Proceedings of the American Society for Engineering Education Conference and Exposition*.

Author et al. (2017). [Details removed for blind review]

Author et al. (2019). [Details removed for blind review]

Authors et al. (2020). [Details removed for blind review]

Bertram, G. W. (2019). *Art as human practice: An aesthetics* (N. Ross, Trans.). Bloomsbury.

Bolton, G., & Delderfield, R. (2018). *Reflective practice: Writing and professional development*. SAGE Publications, Inc.

Brown, P. A. (2008). A review of the literature on case study research. *Canadian Journal for New Scholars in Education (CJNSE/RCJCÉ), 1*(1), 1–13.

Bucciarelli, L. L., & Kuhn, S. (1997). Engineering education and engineering practice: Improving the fit. In S. R. Barley, & J. E. Orr (Eds.), *Between craft and science: Technical work in the United States* (pp. 210–229). Cornell University Press.

Cantero, J. D., Saorin, J. L., Melian, D., & Meier, C. (2015). STELLA 3D: Introducing art and creativity in engineering graphics education. *International Journal of Engineering Education, 31*(3), 805–813.

Colucci-Gray, L., Burnard, P., Gray, D., & Cooke, C. (2019). A critical review of STEAM (Science, Technology, Engineering, Arts, and Mathematics). In *Oxford Research Encyclopedia of Education*. Oxford University Press. https://doi.org/10.1093/acrefore/9780190264093.013.398

Creswell, J. W., & Clark, V. L. P. (2017). *Designing and conducting mixed methods research* (3rd ed.). SAGE Publications, Inc.

Dewey, J. (1910). *How we think*. D. C. Heath & Co Publishers.

Dewey, J. (1915/2001). *The school and society*. Dover Publications.

Dewey, J. (1934/1980). *Art as experience*.: Perigee Books.

Dixon, K., Grzybowski, D. M., Le, J. V., Castro, C. E., Barton, M., & Richardson, O. R. (2017, June). Making meaning through art-integrated engineering. *Proceedings of the ASEE Annual Conference & Exposition*. https://doi.org/10.18260/1-2--28643

Eisner, E. W. (2002a). *The arts and the creation of mind*. Yale University Press.

Eisner, E. W. (2002b). *The educational imagination: On the design and evaluation of school programs*. Merrill Prentice Hall.

Eisner, E. W. (2004). What can education learn from the arts about the practice of education? *International Journal of Education & the Arts, 5*(4), 1–12.

Eisner, E. W. (2005). The role of the arts in cognition and curriculum. In E. Eisner (Ed.), *Reimagining schools: The selected works of Elliot W. Eisner* (pp. 76–85). Routledge.

Eisner, E., & Powell, K. (2002). Art in science? *Curriculum Inquiry, 32*(2), 131–159.

Elo, S., Kääriäinen, M., Kanste, O., Pölkki, T., Utriainen, K., & Kyngäs, H. (2014). Qualitative content analysis: A focus on trustworthiness. *SAGE Open, 4*(1). https://doi.org/10.1177/2158244014522633

Farahian, M., Avarzamani, F., & Rajabi, Y. (2021). Reflective thinking in an EFL writing course: To what level do portfolios improve reflection in writing? *Thinking Skills and Creativity*, *39,* Article 100759. https://doi.org/10.1016/j.tsc.2020.100759

Findley, A., & Mirth, J. A. (2016, June). Enduring design: developing connections between art and engineering. *Proceeding of the ASEE Annual Conference & Exposition*, New Orleans, Louisiana. https://doi.org/10.18260/p.26960

Flick, U. (2014). *An introduction to qualitative research* (5th ed). SAGE

Fwu, B.-J., Chen, S.-W., Wei, C.-F., & Wang, H.-H. (2018). I believe; therefore, I work harder: The significance of reflective thinking on effort-making in academic failure in a Confucian-heritage cultural context. *Thinking Skills and Creativity, 30*, 19–30. https://doi.org/10.1016/j.tsc.2018.01.004

Green, J. L., Camilli, G., & Elmore, P. B. (Eds.). (2006). Handbook of Complementary Methods in Education Research (3rd ed.). Lawrence Erlbaum Associates, Inc.

Guyotte, K. W., Sochacka, N. W., Costantino, T. E., Kellam, N. N., & Walther, J. (2015). Collaborative Creativity in STEAM: Narratives of Art Education Students' Experiences in Transdisciplinary Spaces. *International Journal of Education & the Arts, 16*(15). http://www.ijea.org/v16n15/index.html

Hailey D., Miller A., Yenawine P. (2015). Understanding visual literacy: The visual thinking strategies approach. In D. Baylen & A. D'Alba (Eds.), *Essentials of teaching and integrating visual and media literacy* (pp. 49-74). Springer Cham.

Jonassen, D., Strobel, J., & Lee, C. B. (2006). Everyday Problem Solving in Engineering: Lessons for Engineering Educators. *Journal of Engineering Education, 95*(2), 139–151. https://doi.org/10.1002/j.2168-9830.2006.tb00885.x

Kamp, A. (2020). *Navigating the landscape of higher engineering education: Coping with decades of accelerating change ahead*. Delft University of Technologyand 4TU Centre for Engineering Education. Ehttps://www.4tu.nl/cee/publications/navigating-the-landscape-of-higher-engineering-education-4tu.cee-web-def.pdf

Kerns, S. E., Miller, R. K., & Kerns, D. V. (2005). Designing from a blank slate: The development of the initial Olin College curriculum. In National Academy of Engineering (Ed.), *Educating the engineer of 2020: Adapting engineering education to the new century* (pp. 98-114). The National Academies Press.

Li, W.-T. & Cheng, Y. H. G. (2018). A study on engineering students' creativity through art-infused curriculum. *EURASIA Journal of Mathematics, Science and Technology Education*, *14*(5), 2009–2024. doi:10.29333/ejmste/85867

Li, B., Ryan, R. G., Warter-Perez, N., Gan, Y., Mustafa, H., Cox, H., & Ding, L. (2016). Vertical integration of the liberal arts in engineering education. *Proceedings of the American Association of Engineering Education Annual Conference and Exposition*.

Lönngren, J. (2017). *Wicked problems in engineering education: Preparing future engineers to work for sustainability* [Doctoral dissertation, Chalmers University of Technology]. https://research.chalmers.se/en/publication/250857

Lönngren, J. (2019). Wicked problems in engineering education: preparing future engineers to work for sustainability. *Environmental Education Research, 25*(12), 1808–1809. https://doi.org/10.1080/13504622.2019.1639038

Marshall, J. J. (2013, June). *Learning outcomes from an art-engineering co-curricular course*. Proceedings of the ASEE Annual Conference & Exposition, Atlanta, Georgia. https://doi.org/ 10.18260/1-2--19867

Merriam, S. B. (1998). *Qualitative research and case study applications in education*. Revised and expanded from "Case study research in education." Jossey-Bass Publishers.

Morse, J. (2018). Reframing rigor in qualitative inquiry. In N. K. Denzin & E. S. Lincoln (Eds.), *The SAGE handbook of qualitative research* (5th ed., pp. 796–817). SAGE.

National Academies of Sciences, Engineering, and Medicine (NASEM). (2018). *The Integration of the Humanities and Arts with Sciences, Engineering, and Medicine in Higher*

Education: Branches from the Same Tree. The National Academies Press. https://doi.org/10.17226/24988

National Academy of Engineering (NAE) (2005). *Educating the engineer of 2020: Adapting engineering education to the new century*. The National Academies Press. https://doi.org/10.17226/11338

Ollis, D. F., Neeley, K. A., & Luegenbiehl, H. C. (2004). *Liberal education in twenty-first century engineering: Responses to ABET/EC 2000 criteria*. Peter Lang.

Reilly, J. M., Ring, J., & Duke, L. (2005). Visual thinking strategies: A new role for art in medical education. *Fam Med, 37*(4), 250–252.

Robinson, T. A., Calvo-Amodio, J., Parmigiani, J. P., & Burton, V. T. (2015). Capstone design as an individual writing experience. *International Journal of Engineering Education, 31*(6), 1902–1923.

Roldan, W., Turns, J. A., Arif, A., Tesoriero, G., & Xu, Y. (2019). Students' engagements with reflection: Insights from undergraduates. *Proceedings of the ASEE Annual Conference & Exposition*, 13. https://doi.org/10.18260/1-2--33313

Saldaña, J. (2013). *The coding manual for qualitative researchers*. SAGE.

Sánchez-Martí, A., Sabariego Puig, M., Ruiz-Bueno, A., & Anglés Regós, R. (2018). Implementation and assessment of an experiment in reflective thinking to enrich higher education students' learning through mediated narratives. *Thinking Skills and Creativity, 29*, 12–22. https://doi.org/10.1016/j.tsc.2018.05.008

Schön, D. A. (1983). *The reflective practitioner: How professionals think in action*. Basic Books.

Schön, D. A. (1987). *Educating the reflective practitioner: Toward a new design for teaching and learning in the professions*. Jossey-Bass Publishers.

Schwandt, T. A., & Gates, E. F. (2018). Case study methodology. In N. K. Denzin & E. S. Lincoln (Eds.), *The SAGE handbook of qualitative research* (5th ed., pp. 341–358). SAGE.

Seager, T., Selinger, E., & Wiek, A. (2012). Sustainable engineering science for resolving wicked problems. *Journal of Agricultural and Environmental Ethics, 25*(4), 467–484. https://doi.org/10.1007/s10806-011-9342-2

Sepp, L., Orand, M., Turns, J., Thomas, L., Sattler, B., & Atman, C. (2015). On an Upward Trend: Reflection in Engineering Education. *Proceedings of the American Society for Engineering Education (ASEE) Annual Conference*, 13. https://doi.org/10.18260/p.24533

Shuster, M. D. (2008). The arts and engineering [Focus on Education]. *IEEE Control Systems Magazine, 28*(4), 96-98.

Sochacka, N. W., Guyotte, K. W., & Walther, J. (2016). Learning together: A collaborative autoethnographic exploration of STEAM (STEM+ the Arts) education. *Journal of Engineering Education, 105*(1), 15-42.

Stake, R. E. (1995). *The Art of Case Study Research*. SAGE.

Svyantek, M. V., Kajfez, R. L., & McNair, L. D. (2015). Teaching vs. research: An approach to understanding graduate students' roles through ePortfolio reflection. *International Journal of ePortfolio, 5*(2), 135–154. https://eric.ed.gov/?id=EJ1107857

Turns, J. A., Shroyer, K. E., Lovins, T. L., & Atman, C. J. (2017). Understanding reflection activities broadly. *Proceedings of the American Society for Engineering Education (ASEE) Annual Conference*, 21. https://doi.org/10.18260/1-2--29054

Wendell, K. B., Wright, C. G., & Paugh, P. (2017). Reflective decision-making in elementary students' engineering design. *Journal of Engineering Education, 106*(3), 356–397. https://doi.org/10.1002/jee.20173

Wood, A., & Martello, R. (2020). Work in progress: Liberal arts help engineering students change the world. *Proceedings of the American Association of Engineering Education Annual Conference & Exposition.*

Yenawine, P., & Miller, A. (2014). Visual thinking, images, and learning in college. *About Campus, 19*(4), 2–8. https://doi.org/10.1002/abc.21162

Appendix: Sample Protocols for Semi-structured Interviews

Interview 1 (conducted at the beginning of the semester)

About yourself:

1. Tell me about yourself. How do you see yourself? What kind of person do you think you are?

About reflection:

2. Please tell me what you think about reflection.
3. What do you think reflection is? How reflective are you in general? How often do you reflect? What do you usually reflect about? What makes you reflect? Do you reflect while you're working on something? If you do, can you tell me an example?

Regarding your thoughts about the arts and humanities:

4. What do you think about the arts and humanities in relation to yourself? How much (often) are you engaged in the arts or humanities in your life? What kind of arts?
5. What do you think about the arts and humanities in relation to engineering?

Regarding the course:

6. What made you enroll in this class?
7. What is your thought about this course? What do you expect to learn from the class?
8. Do you have any concerns? Suggestions about the course?

Regarding being an engineer:

9. What made you interested in becoming an engineer? Do you have an anecdote you want to share?
10. What is your image of an engineer?
11. What kind of an engineer do you want to become? For example, what do you see yourself doing? What are the key qualities/characteristics of your future self?
12. Anything else you want to share? Concerns? Suggestions?

Interview 2 (conducted at the end of the semester)

About Reflection:

1. After taking this course, what do you think about reflection in general now? Are there any changes about your reflective thinking/reflective actions thanks to the class? If so, can you give an example? If no changes, why do you think it is the case?
2. What is it that you learned about reflective thinking in engineering that you didn't know before?
3. What course activities helped you the most in becoming reflective and why?
4. What course activities helped you the least in becoming reflective and why?
5. How do you think you'll apply the knowledge of reflection to your personal and professional life in engineering?

About the arts and humanities:

6. After taking the course, what did you learn about the role(s) that the arts and humanities can/may play in relation to your personal life?
7. After taking the course, what did you learn about the benefits that the arts and humanities can offer you in being and becoming an engineer?
8. After taking the course, what roles do you think the arts and humanities can play in helping you become more reflective or not?

About the Course:

9. What did you learn from the course?
10. What benefits/advantages/disadvantages do you think this course provided you?
11. What was the strength of the course that enhanced your learning about reflection?
12. What was the weakness of the course that hindered your learning about reflection?
13. Did the course content meet and challenge your intellectual, social, cultural, and emotional levels and expectations? If not, what would be your suggestion?
14. How did you like the way the course was taught? What suggestions do you have?
15. If you would take this course again, how would you, as a learner, approach it?

About being/becoming an engineer:

16. Do you think the course will influence, has influenced, or will not influence the kind of engineer you want to become? Can you explain why?
17. Did the course affect your image of an engineer? If there is a change, what would it be?

Table 1. Emerging themes and associated data sources

Figure 1. Group 1 students' artwork and artist statement: At the mercy of mercury

Figure 2. Group 2 students' artwork and artist statement: The fifth leg of the cat

Figure 3. Group 3 students' artwork and artist statement: BEElieve