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Lessons Learned from a First Attempt to Teach Systems Engineering as a Studio Art Class

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Introduction

System architecture can be considered both an art and a science [1], [2]. Whereas its scientific side deals with producing actual designs, its artistic one drives the value of the system architecture [3]. In fact, using elegance as a key driver in architecting engineering systems may provide significant benefits over following traditional processes [4]–[6]. This is in line with expertise research, which shows that effective systems engineers exhibit strong ability on both sides [2], [7]. However, the development and training of systems engineers tend to focus on the analytical and methodological side. The question of how we ought to teach the artistic side of systems engineering arises. Prior work suggests there is overlap between some of the key competencies systems architects should have with those required for artists [8]. This insight was used to suggest a plan to teach systems engineering using a studio art approach, as employed in the arts, rather than the traditional instructional approaches employed when teaching engineering sciences [9].

In this paper, we will report what happened in the first semester where the studio art approach was implemented in a systems engineering course. We collected both quantitative and qualitative feedback from students to understand how they responded to the new course format. As often occurs when trying a new teaching method, there were several bumps along the way as the instructor learned to teach using the new format. Thus, the purpose of this paper is to report how students responded to the studio art course format and provide insight from the instructor about the challenges he faced during the implementation. We will conclude with recommendations for anyone interested in implementing this format in their own courses.

Related Literature

The engineering education community-at-large has called for an increased focus on developing the creativity and innovative thinking skills of engineering students [10]–[12]. In particular, skills such as observation, problem finding, divergent thinking, and iterative experimentation have been suggested as necessary for creative engineering work [10], [13]–[16]. However, traditional engineering education may actually reduce the level of creativity in designs produced by students [17], [18]. Alternative pedagogical methods have been explored for improving engineering student creativity, including open-ended projects and collaborative activities [15]–[17]. Others have pursued interdisciplinary courses, where engineering students work with art students or take classes from art instructors [19]–[21]. Only a limited number of engineering courses have pursued the studio art course format as a potential method for teaching, primarily design-focused courses where the learning outcomes are most similar to those in the arts [22]–[24]. No one has yet reported a full implementation of an engineering course using the classroom setting, lesson structure, and course structure of a traditional studio art class.

We have argued previously that systems engineering concepts are relatively easy to teach to students [9]. Some even suggest that systems engineering is simply good engineering [25]. However, what seems simple to understand becomes more challenging when students and professionals attempt to put systems engineering into practice. This is in contrast to traditional engineering sciences, where students may struggle to learn the concepts, but once achieved they can be easier to apply in practice. In systems architecture, for example, students are taught to "simplify" their designs [1], but simply knowing that simplification is necessary does not result in effective simplification in practice. Applying the concept of simplification in the process of creating a system architecture is an *art* that requires repeated, iterative practice with feedback. This is why we believe that a systems architecture course is a good candidate to be taught using the studio art format [9].

Similar practices have been identified between system architects and both composers of film scores [26] and master painters [27], including managing complexity and seeking harmony in the final product. A full mapping between competencies needed in the arts and systems architecture revealed that a similar problem is faced in the art education world: concepts such as the color wheel are easy to teach, but few people can take these concepts and create a master piece of artwork [28]. However, unlike in systems engineering, art instructors have designed their courses to address this fact. Art courses are held in classrooms where artwork can be displayed for all to view and critique, time is spent in class working on art projects, and then the class provides feedback to each other [9]. Such interaction and feedback should be an important component of systems architecture education, because the process of developing an architecture should involve understanding multiple perspectives on a problem [29]. In this paper, we describe a systems engineering course that has been adapted to follow the structure commonly found in studio art courses and the lessons learned through the first implementation of this teaching strategy.

Course Description and Studio Art Implementation

The studio art approach was implemented in the ENGR 5004 Systems Engineering Process graduate course in Fall 2018. The course is designed as the first step in Virginia Tech's systems engineering program to make students become effective systems engineers. Despite its name, the course intent is not to describe a process. Rather, the course focuses on understanding systems engineering as a strategy-driven discipline, where success is ultimately achieved by effectively and efficiently identifying, framing, and executing a number of concurrent and sequential choices. Treating the system as a black box, the course stresses the importance of distinguishing between operational need and system solution. Students are provided with the necessary mindset, thinking processes, and tools and techniques to identify a need, envision alternatives, choose a solution, and materialize it.

Table 1 lists the sequence of contents of the course. The studio art approach was used to some extent to cover topics 4 through 11, with its deepest application in Topic 11 - System architecture.

Table 1. Course content

Order	Topic
1	Systems and systems engineering
2	The system life cycle
3	A technical strategy perspective
4	Effort allocation
5	System operation

6	System deployment
7	System retirement
8	Problem formulation
9	Verification and validation
10	System acquisition and integration
11	System architecture
12	The people side of systems engineering

The approach was based on the plan described in [9]. Because of the course content described in Table 1, only the lesson structure was implemented. Its basic structure was as follows:

1) *Lesson*: The instructor explained basic concepts such as the function/form distinction or the conditions for well-formulated requirements.
2) *Practice*: Students spent time applying the concepts, such as to define problems or to architect a solution to a given problem. The instructor provided feedback to students individually as they practiced their systems engineering skills. Feedback was provided in real-time for face-to-face students.
3) *Expositions*: Towards the end of the lesson students shared their work and compared it holistically. Students were then asked to find strengths and weaknesses in the work of their peers.

There were a number of challenges that the instructor faced in this first attempt to use the studio art approach:

First, several other changes were implemented in the course together with the overall approach, including course content and topic sequence. This made it difficult to assess how the studio approach affected overall student outcomes.

Second, a fully asynchronous delivery was offered for the first time for remote students. Microsoft OneNote was used as the main vehicle to provide the content. Basic concepts were provided in the form of slides and notes. Students worked, sometimes individually and sometimes in groups, using the whiteboarding capability of the platform. The instructor provided feedback directly in the platform. However, the dynamic was not as smooth as desired. Additional synchronous sessions had to be scheduled. Several issues may have contributed to this. Course schedule, in terms of dates for covering material and submitting homework, had to be frequently revisited to adjust the course content to the new delivery format. Assignments were too vague. While these worked nicely (for learning purposes) in face-to-face classes, which have a very direct interaction, they caused significant delays for remote students to receive the necessary feedback from the instructor. As a result, the desired group dynamics were not achieved. Freedom in the way students could deliver their assignments required significant effort from the instructor to generate valuable feedback, which also negatively affected the dynamic of the assignments.

Third, this was the first attempt to deliver the course in this novel format. Furthermore, it required changing only delivery format for material that had been taught by the same instructor differently in previous years. The learning curve was steep and a pilot program was not conducted in advance. As a result, instruction was not as smooth as planned.

Methods

To evaluate how students responded to the studio art course format, we administered a survey in the second half of the semester. This survey combined an inventory assessing student motivation [30] with several open-ended questions seeking student feedback about the course.

MUSIC Model of Motivation. The MUSIC model synthesizes a broad array of motivation research into five components that instructors can incorporate into their courses to improve student motivation [31]. *Empowerment* describes the amount of perceived control students have over their learning in a course. *Usefulness* emphasizes the need for students to understand how course content applies to them and their career goals. *Success* suggests that students need to be able to succeed at all aspects of the course if they invest the necessary effort. *Interest* refers to the influence that instructors can have on student interest in their course through classroom activities and instructional choices. *Caring* underscores the need for students to believe that their instructor cares about their learning [30]. As a whole, the MUSIC model highlights the direct connections that exist between instructional decisions and student motivation in a specific course.

Data Collection. To assess the five dimensions of student motivation, the MUSIC Inventory was developed and validated across a wide variety of student populations [31]. The inventory includes 26 questions which students rate on a scale of one ("Strongly Disagree") to six ("Strongly Agree"). The MUSIC inventory was included as the first portion of our survey. We also wanted to understand how students were responding to the studio art course format in their own words, so we included four open-ended questions at the end of the survey. These questions were:

- What do you appreciate about the course structure for [course name]?
- What is challenging or frustrating about the course structure for [course name]?
- How can you engage more actively in this course?
- How can the instructor better support your learning in this course format?

The survey was administered through an online survey development website hosted by the university. The graduate student researcher on the project visited class one week to introduce the study and answer any questions students might have (while the instructor was not in the room). She also coordinated the survey data collection and did not share the results with the instructor until after grades were submitted at the end of the semester. This study was approved by the institution's IRB.

Participants. Eight students responded to the survey out of the 11 total enrolled in the class. We had an even split of students who were enrolled in the in-person class and those taking the class remotely. All students were graduate students early in their master's or PhD programs, mainly within the Industrial and Systems Engineering department. Most of the students taking the class in person are full-time graduate students, while most of the students taking the class remotely are part-time students who work full-time at engineering jobs.

Data Analysis. For the MUSIC Inventory, we found the average score for each of the five dimensions for the whole class, the remote students, and the in-person students. We did not have a comparison point to understand how student motivation in this class compares to other classes or changed over the course of the semester. However, we were able to compare scores across the five dimensions (to understand if certain dimensions were notably lacking or strong) and compare between the two student groups. We then reviewed the open-ended responses to identify themes in student comments to better understand how students were responding and thinking about the studio art format of the course.

Limitations. Given that this was the instructor's first time teaching using the studio art method, the class experienced some challenges as he learned and adapted to using this style of teaching. Thus, our results provide little insight into the effectiveness of the studio art teaching format in achieving course learning outcomes. However, we believe that the insights provided by the students and the instructor give useful perspective and lessons learned to others interested in attempting this course format.

Results: Student Perspective

Implementing a new course format can often lead to pushback or negative responses from students, particularly if the instructor is requiring more active participation in the classroom [32]–[34]. This is partially why we wanted to gather data both about student motivation in this course and get their feedback about the new course format. We report the results of each method below.

Student Motivation. Table 2 shows the average score on each of the five dimensions of the MUSIC model of motivation for all survey respondents, in-person students, and remote students.

Table 2. Student Motivation Survey Results

Dimension	Avg. All Students	Avg. In-Person	Avg. Remote
Empowerment	4.58	4.70	4.45
Usefulness	5.05	4.80	5.30
Success	4.97	5.19	4.75
Interest	4.81	5.04	4.58
Caring	5.44	5.58	5.29

Note: Scale is from one ("Strongly Disagree") to six ("Strongly Agree")

Although we cannot make claims about changes in students' motivation, it is encouraging to see that the averages are relatively high across the board. In fact, these scores are equivalent or higher than MUSIC model scores reported in other recent studies of student motivation in courses implementing pedagogical innovations (e.g., [35], [36]). At the very least, this indicates that implementing the studio art course format probably did not result in a significant drop in student motivation. Further, it is encouraging that the highest score overall is in the "Caring" dimension, suggesting that students had a positive view of the instructor and his desire to help them learn. Implementations of active learning strategies can sometimes lead students to blame the instructor for asking them to take more responsibility for their learning. Happily, this does not appear to be the case for these students.

Given the challenges faced in adapting the studio art format for the remote students, it is particularly encouraging that their motivation scores are generally close to those of the in-person students. The only dimension where there is a half-point difference in average scores is for the

Usefulness dimension, where the remote students have the higher average. This may be related to the fact that many of them are working professionals and therefore may see more immediate applications of the concepts they are learning in class. In total, then, it seems that students had a generally positive experience in the course as measured through the MUSIC model of motivation. We explored this further through analysis of the open-ended feedback questions.

Student Feedback. Supporting the findings from the motivation survey, the open-ended questions revealed that students generally had a positive view of the course format. Two positive aspects of the course and one challenge emerged as common themes across students, described in the following sections.

<u>Interactive Course Format</u>

Several students discussed the fact that they appreciate how this course allows them to see how other students are approaching the same problems. Students felt that this helped them ask questions, check their own understanding of the material, and have more chances to ask questions. For example, one student explained that:

"Getting to engage with the material and get real time feedback, and see how others are working through problems as we work through problems is great."

While another suggested that:

"I feel like it truly helps in learning. Traditional class settings do not really measure if you understood or not. In this class, if you do not understand, the instructor and you as a student can truly understand."

Overall, students seemed to see the benefits of have a more interactive course format compared to traditional lectures, which is an excellent outcome compared to what has sometimes been reported in the literature.

<u>Open-Ended Problems</u>

The second theme that appeared across responses was that students appreciated the open-ended nature of the assignments and class discussions. Although some did suggest that there could be more structure around logistics such as due dates or grading rubrics, they generally seemed to understand that open-ended problems better prepare them for engineering work. For example, one student commented that:

"It is representative of how things work in a non-academic environment. It requires students to ask questions to come to their own outcomes and not just attempt to get to an answer."

Similarly, one student explained that:

"Personally I enjoy the LACK of structure for this course. [. . .] I think it allows us to be much more flexible and focus on actually learning the material and how to apply it to the real world rather than be forced to memorize material in some fashion just for the sake of evaluations or exams."

Thus, despite some concerns about logistics (discussed in the next section), students were able to appreciate that the more open-ended types of problems presented in this course were useful in learning the course content more thoroughly.

Need for Feedback

As discussed earlier, there were some challenges in implementing the studio art course for the first time. This was reflected in the student comments most prominently in terms of their suggestions that more feedback was needed on the assignments. Although they tended to believe that the open-ended assignments were useful, they suggested that they could get more out of them with more thorough and prompt feedback. One remote student summarized this clearly, saying:

"The open-ended assignments are a great way to make us grapple with the concepts and make sure that we actually understand the concepts, but in order for those to be effective, we need way more feedback. I have often felt like I was very unsure of the answers I was providing for the assignments, but the schedule and the lack of feedback meant that I had to spend a lot of time working on my solutions before I found out that I was totally wrong."

This concern was particularly strong for remote students, since their interactions with the instructor were not as regular as the students coming to class every week. One student noted that this was a challenge (although it improved over time), saying:

"In the beginning I felt things were more unclear than they needed to be especially as a remote student. Not being in class at least once per week makes it harder to interact and work through problems with the professor and get immediate feedback. The more recent changes that were made have been helpful."

Providing thorough feedback is more challenging in a class with open-ended assignments. Having in-class discussions can be helpful in mitigating this, however it is clear that students in this class needed more feedback to feel confident in their understanding of the course concepts.

Results: Instructor Perspective

Assessing the impact of the proposed studio art approach on the quality and characteristics of the students' assignments was not possible because of the potential confounding effects of the changes and challenges previously identified. However, the in-class sessions still provided some insights of some of the effects of the proposed approach. Originally, the studio art approach, and in particular the *exposition* phase, was expected to "enable students to gain exposure on how different solutions could have worked" [9]. We describe now the instructor's insight during those sessions. Three areas are worth discussing: student critique of the solutions of others, internal assumptions, and modeling technique.

Asking students to evaluate the solutions of other students showed very interesting results. In a professional setting, critiquing, especially with the aim of finding holes, gaps, and problems, is a critical activity of the systems engineers. However, students had a major problem at first to criticize the work of other students. Although we do not make any claims about the source of this problem, we speculate that it might be because of the mental models created by the education system, a willingness to avoid confrontation in an inclusive environment, or simply to avoid criticizing a classmate in front of the instructor. Nevertheless, the instructor's perception is that students had a hard time initially with pointing out the weaknesses in their classmates' work. Once this first roadblock was overcome, students would point out elements from their own solutions that other students had missed. In other words, the students took their own solutions as a sort of benchmark and assessed if another student had similar elements in their solution. We believe that this is a meaningful first step in assessing the work of others, since the student is building on his/her experience to find discrepancies (eventually patterns) between that and the new work that is subject to evaluation. Interestingly enough, towards the end of the semester, as the students became (we contend) more comfortable in the *exposition* sessions, their feedback would in addition center on evaluating their classmates' work on the basis of *that work*, not only on their own experience. In other words, the students moved beyond simply finding discrepancies with respect to their own mental models and experiences and began to evaluate the solution holistically and independently. This indicated an increased understanding of gaps and inconsistencies offered by the models available and the mental models of the other student.

Students trying to understand each other's mental models as a means to make sense of each other's solutions was a departure from traditional instructional approaches in engineering. As the course progressed and students became (we contend) comfortable participating in expositions, the instructor observed that they leveraged the internal assumptions of their classmates to understand the meaning, scope, and reach of their solutions, beyond what they had modeled or a drawn. Conversations between students to unveil these internal assumptions, with the aim of achieving consistency in understanding, showed that the student acting as evaluator would gain additional insights as to how the problem could be solved and the student receiving the evaluation realized how their own work could be interpreted differently by different people.

Class discussions suggested that drawings (models) were instrumental in facilitating the students' learning of the existence of different internal assumptions and solutions to the same problem. A specific modeling language was not enforced in the course. This was done purposefully to let students *draw* their solutions without modeling or diagrammatic constraints. For example, one student would always take a more artistic representation in his/her models, such as drawing different faces to represent different stakeholders. Another student used several colors to depict and distinguish multiple viewpoints in a single drawing. Another student opted to split the model in several instances, which would cover several scenarios of his/her solutions. The interesting aspect of this is that the class could see how these different approaches led to both specific strengths and weaknesses in the solutions developed by these students.

Discussion and Recommendations

The first attempt at teaching this systems engineering course using the studio art approach revealed both strengths and challenges. It was encouraging to see that students generally enjoyed the course format and seemed to understand the benefits associated with a more open-ended structure. Student resistance can be a problem when introducing new pedagogical strategies, although implementing the change in a graduate course may have eased the transition [33]. This is particularly noteworthy given the discomfort students seemed to have experienced initially in being asked to critique the work of their classmates. In traditional engineering group projects, students are rarely invited to provide this kind of feedback to each other, so it is understandable that they might find it challenging. However, the format of the course allowed students to experience feedback from the instructor in the same manner, perhaps giving them an example of how to frame their ideas and suggestions. Students may also have become more comfortable with critique as they came to realize that the open-ended types of problems addressed in this course do not have a single correct answer. This shift away from the traditional structured problems of many engineering courses can also require adaptation for students [37].

The introduction of the *exposition* sessions in the course allowed students to see not only the process by which their classmates approached problems, but also explore their varying assumptions and mental models. Traditional engineering courses tend to present information from a *positivist* perspective, which suggests that the course content is a set of objective information that the instructor can impart to the students and there is one correct way to solve each problem. In contrast, the *constructivist* perspective acknowledges that each individual brings their own understanding of reality (i.e., mental models) to the problems they try to solve [33], [38]. Although some engineering courses may adopt pedagogy that works from a constructivist perspective, it is rare that students have a chance to truly engage with each other's mental models. Such engagement is essential in the cross-disciplinary and multi-stakeholder environments that systems engineers work in everyday [39], [40]. Developing the ability to view a situation from an alternative frame of reference can improve the ability of systems engineers to truly understand stakeholder needs and requirements. Thus, we are particularly excited to see that the studio art course format seems to encourage this type of interactive learning that is realistic to the work environment [41].

Based on this initial implementation of the studio art course format, we have several recommendations for instructors interested in trying this method in their own courses. First, as clearly indicated in the student comments, feedback is a central component of adapting this teaching approach, so it is important to provide it regularly and promptly. Not only does this provide students with feedback on their work, it also provides an example of the types of critiques they could introduce into the *exposition* sessions in class. Second, it may be helpful to show solutions from the instructor periodically in the class. Although critiquing each other's work is helpful, sometimes there may be concepts that many or most students will miss. In these cases, having an instructor example to analyze together may help the students identify the missing pieces on their own through discussion. Third, because much of the class time is dedicated to working on example problems and having exposition sessions, it is important that students complete pre-reading to gain some of the basic information for the course. This should ideally be balanced by the fact that homework problems are worked out in class, but if students neglect to prepare for class, it is hard to approach the problems at all. Thus, it may be necessary to introduce reading quizzes or other *incentive* to ensure that students prepare sufficiently before class. Finally, although the problems for this type of course are necessarily open-ended, it is still important to provide clear information about what needs to be done for each course assignment. This may take the form of a rubric or a list of requirements; anything that communicates enough information to students that they can focus on working on the problem rather than worrying about how to present the information.

Conclusion

We learned a lot through the initial attempt at implementing the studio art approach in a systems engineering course. Although the instructor faced some challenges in transitioning the course to the new format, there were several positive outcomes. Students found the new format engaging and seemed to recognize that the activities used in class were relevant to real work environments. Additionally, the instructor found that the class discussions allowed for unique student interactions rarely seen in engineering classrooms, allowing students to view problems from different perspectives. We feel that these outcomes support further attempts to refine this teaching approach and will continue to explore this approach in future offerings of the course.

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