A Systems Approach to Teaching Engineering Design to Non-Engineers

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Abstract – To determine the effectiveness of taking a systems approach to teaching engineering design to non-engineers, a mixed methodology was implemented that consisted of analysis of weekly reflections and retrospective posts. The participants of this study were fellows of the National Center for Engineering and Technology Education that were enrolled in the course, "Engineering Design: Synthesis, Analysis, and Systems Thinking." To assess the change in the student's understanding of engineering design throughout the semester, students were asked to complete a retrospective post. The reflections and survey results were combined to determine the effectiveness of employing a systems approach to teach design to non-engineers. A significant result of this research project was that introducing engineering design using a systems approach to non-engineers was effective. If this is true for other K-16 non-engineers, design can be integrated into every student's learning experience whether they are studying English and history, or math and science.

Keywords: Systems thinking, Design, Non-engineers.

INTRODUCTION

The goal of the National Center for Engineering and Technology Education (NCETE) is "to infuse engineering design, problem solving, and analytical skills into the K-12 schools through technology education in order to increase the quality, quantity, and diversity of engineering and technology educators, and to significantly strengthen the pathways to engineering and technology professions for students [21]." This research project was developed to assess the effectiveness of using a systems approach to teach engineering design to non-engineering NCETE fellows. Fellows of the National Center for Engineering and Technology Education are required to take a series of four courses taught at each of the four doctoral institutions. The University of Georgia taught the third course, "Engineering Design: Synthesis, Analysis, and Systems Thinking," in this series in the Fall of 2006. In this course, non-engineering students were taught engineering design using a systems approach. Because this course is taught to students at four different institutions, video-conferencing software (Macromedia Breeze) was used and the course was broadcast over the Internet. There were three aspects of the course that were used to teach engineering design using a systems approach, (1) weekly readings on systems thinking with weekly reflections written based on these readings, (2) systems and engineering design lectures and student-led discussions that were held at the weekly class meetings, and (3) an ill-defined engineering design team project. The first two aspects of the course were used to provide background for the students in systems and engineering design. The third aspect of this course, the ill-defined engineering design project was used to immerse the students in a design experience over the course of the semester. The students were given the following problem statement*: A rural village in Pocora, Costa Rica, currently has a water delivery and wastewater collection system that is not meeting the needs of the community with respect to water quality and environmental health.* From this very ill-defined problem statement the students were divided into three inter-institutional teams and were charged with developing an engineering design project.

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Systems Overview

A shift in the basic philosophy of nature developed by Francis Bacon, Renè Descartes, and Isaac Newton, has been suggested but for the most part rejected within mainstream science. It adheres to a view of nature as a deeply organic and connected system of relationships that is not necessarily or readily submissive to reductive thinking and analysis **Error! Reference source not found.**[4][5]**Error! Reference source not found.**[17]**Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.**[25][26][27]. Mission statements of institutions of higher learning often include the academic charge "to inquire into the nature of things". This is quite revealing as to society's current view of nature, particularly within academia. That is, it is comprised of things into whose nature we can inquire. The fields of physics, chemistry, biology, and ecology have informed society over the past several centuries and improved the standard of living in many societies to its current level through rigorous adherence to Baconian-Cartesian-Newtonian philosophy and application of the scientific method whereby nature is manipulated to provide the human species with life-sustaining services [6][15]. Our understanding of how nature works within the context of ecosystem has clearly been leveraged as envisioned by Bacon, who believed that nature was to be "hounded in her wanderings," "bound into service," and made a "slave"; she was to be "put in constraint," and the aim of the scientist was to "torture nature's secrets from her [5]." In the wake of Bacon's worldview, we can point to engineering as one human activity by which some of the secrets of nature have been leveraged to serve humanity at scales ranging from nano- to landscape. The traditional engineering disciplines have matured in large part because of the success of the scientific method in isolating objects from nature, learning their behaviors under controlled conditions and subsequently designing systems of parts that maintain these conditions and provide a function to society that is predictable, controllable, and safe for humans [16]. This leads us to one of the premises of this research; that being, the traditional isolated approach to understanding nature is mimicked in current educational systems. We propose that such isolated schema are discouraging to women and minorities whose backgrounds, cultures and life experiences may resemble a more connected, living and nurturing system that is perhaps more complex than the crisp and simple Newtonian models. Again, while this research is not suggesting that the rigor of Newtonian thinking be abandoned, it is suggesting that perhaps a significant sector of U.S. society is being inadvertently and unnecessarily discouraged from pursuing engineering as a profession due to an overemphasis on analysis and an under-emphasis on complexity. Engineering design is often taught in a very Newtonian way, with an overemphasis on analytical tools and a disregard for the complexity inherent in engineering design.

Engineering Education Overview

During most of the twentieth century, stakeholders from the engineering community have noted a disjuncture between engineering education and engineering practice. The competencies, knowledge, skills, and abilities that students learned in their undergraduate engineering curricula aligned poorly with those needed by practicing engineers. As early as 1918, the Carnegie Foundation reported industry's concern regarding the state of engineering education [18]. Their results indicated that the greatest area for improvement in engineering programs lie in the human and social dimensions, specifying communication skills, business sense, and interpersonal skills. After almost three-quarters of a century, concerns raised by the Carnegie Foundation study are mirrored in survey results of Evans et al. pointing to the growing need of engineers to possess human and social skills over both breadth and depth of technical skills. In October 2006, Charles Vest, the next president of the National Academy of Engineering echoed these concerns in the Brunel Lecture Series on Complex Systems at Massachusetts Institute of Technology [24]. There is general consensus among engineering experts that engineering students should be prepared to analyze problems, design under varying non-technical constraints (e.g., social or environmental), communicate with people outside of their specific discipline, and remain lifelong learners in a rapidly changing world [2][3][8][9][10][12][19][20][22][23][28]. Engineering educators are in agreement over the broad competencies that engineering graduates need, but have had little success in infusing change. Moreover, this needed change does not appear on the near horizon, although more and more people and resources are being spent on engineering education research.

As Technology Education proposes to integrate engineering design into their curriculum, it is important that they do not mimic engineering design as it is taught in undergraduate engineering education courses. If engineering design is taught the way it is taught in undergraduate engineering education courses, then the same problems that have been pervasive in engineering education will be transferred to Technology Education. Additionally, when teaching students that have not made the commitment to study engineering, there is a larger chance that they will quickly disengage from engineering design if they view it as being purely technical and analytical, with no connection to the outside world or to people. A systems approach to teaching engineering design inherently includes aspects of engineering beyond the purely technical and analytical ones. A systems approach to engineering design necessitates considering the social, cultural, environmental, global, and economic aspects of an engineering design project in addition to the technical and analytical aspects. Charles Vest, the next president of the NAE, explained that, "Although we cannot know exactly what they should be taught, we can focus on the environment in which they learn and the forces, ideas, inspirations, and empowering situations to which they are exposed [24]." Even if the systems approach to engineering design is not the best approach to teaching engineering design, it does change the students' learning environment from a very brittle, rigid one into an open, passionate, inspirational, and empowering one.

Research Purpose

The authors examined the following research question:

To what extent is it effective to take a systems approach to teaching engineering design to non-engineers?

To answer this broader question the following series of questions will be answered:

1. To what extent did the students learn fundamental concepts of engineering design?
2. To what extent do the students understand systems thinking and its relationship to engineering design?
3. To what extent do the students believe that the systems approach is an effective way to teach engineering design?

RESEARCH DESIGN

The research design section will discuss the study participants, the methodology, and the study variables and analysis. This research was completed in compliance with the Institutional Review Board.

Epistemology

Constructionism is the epistemology underlying this research. Constructionism is "the view that all knowledge, and therefore all meaningful reality as such, is contingent upon human practices, being constructed in and out of interaction between human beings and their world, and developed and transmitted within an essentially social context" [7]. This research reveals useful interpretations, but does not reveal ultimate truths.

Participants

The participants of this study are graduate student fellows of the National Center for Engineering and Technology Education. The course, "Engineering Design: Synthesis, Analysis, and Systems Thinking" is the third in a series of four courses that are required for the fellows. Of the 12 graduate student fellows in the course, 11 agreed to participate in the study, all of which returned the survey. The average age of the participants is 34 and nine of the participants are male (82%). Most of the participants have Technology Education and research experience (10 of 11 students or 91%), however very few have engineering experience (2 of 11 have engineering experience, 1 of 11 has an undergraduate engineering degree).

Methodology

To assess the effectiveness of a systems approach to teaching engineering design to non-engineers, a methodology is used that consists of end-of-the-semester surveys with retrospective post and open-ended questions (see table 1). The retrospective post results are analyzed using a Microsoft Excel spreadsheet. The researchers calculate the averages for each of the retrospective post questions and a difference of 0.5 or greater is considered to be a significant difference. Additionally, the researchers calculate the net change in participant responses and display these results graphically. The researchers then analyze the open-answered survey results using NVivo 7, a qualitative analysis software package. The effectiveness of employing a systems approach to teach design to non-engineers is then determined based on this analysis.

Table 1. Research sub-questions with corresponding retrospective post statements and open-ended survey questions

Research sub-question	Retrospective post statement	Open-ended survey question
To what extent do the students understand fundamental concepts of engineering design?	I have a *basic* understanding of engineering design. I have a *deep* understanding of engineering design. I understand the engineering design process. Without strong math and science skills one cannot contribute to engineering design. To add to an engineering design team, I must have a strong background in math, science, and engineering sciences. I have an understanding of the similarities and differences of engineering science and engineering design.	Describe the similarities and differences between engineering science and engineering design. How has your perception of engineering design changed over the course of this semester?
To what extent do the students understand systems thinking and its relationship to engineering design?	A systems approach to engineering design is inclusive of reductionist methods. I have an understanding of the systems worldview and its relationship to engineering design. I have an understanding of the reductionist (Newtonian) worldview and its relationship to engineering design.	Describe the systems approach to engineering design.
To what extent do the students believe that the systems approach is an effective way to teach engineering design?	A strictly reductionist (Newtonian) approach to teaching engineering design would be effective. A systems approach to teaching engineering design is effective. *Engineering Education* would be improved with systems-thinking concepts included in the teaching of engineering design. *Technology Education* would be improved with systems-thinking concepts included in the teaching of engineering design. A strictly reductionist (Newtonian) approach to teaching engineering design to K-12 students would be effective. A strictly reductionist (Newtonian) approach to teaching engineering design would be an epistemologically-closed learning environment. A systems approach to teaching engineering design to K-12 students would be effective.	In your experience, how effective is a systems-based approach to teaching engineering design? Please explain. If teaching engineering design to a group of high school technology education students, would you take a systems and/or a reductionist (Newtonian) approach? Please explain.

The participants' responses to the survey are metacognitive in nature because participants are reporting their learning about systems and engineering design. In a retrospective post, students complete a survey that inquires about both their self-perceived levels of knowledge at the end of the semester, and their estimation of what their levels of knowledge were before learning occurred. This type of data collection method was used because research has shown that a retrospective post is more effective when measuring self-perceived levels of knowledge because of the inability of the students to know their deficiencies in a particular subject before taking a course.

To begin analysis of the open-answered questions, the authors reviewed online survey open-ended question responses and interview transcripts to develop descriptive codes. To establish trustworthiness, the first author coded and then re-coded the transcriptions three weeks later. To ensure inter-rater reliability, the authors ensured that a firm coding scheme was in place before coding the data. The firm coding scheme was developed by the first author, reviewed and revised by the research team, and applied to a sample of the open-answered responses by the research team. The coded interview transcriptions were then compared, and the coding scheme was revised. Another set of interview transcriptions were coded by the research team, and the resulting codes were comparable. At this point, the first author used this established coding scheme to code the remaining transcriptions. This author consistently applied these codes to the data set. These codes were then reviewed to determine patterns within the transcriptions.

RESULTS

Results of this study indicate that teaching design to non-engineers using a systems approach is effective. This was determined by studying how well the students learn fundamental concepts of engineering design, whether they feel that engineering design should be infused in the K-12 curriculum, how well they understand integrating systems thinking and engineering design, and whether they plan to use the systems approach to teach engineering design. To determine these answers, the students' responses to survey questions are grouped accordingly and analyzed. All of the participants' comments on the survey are considered to be metacognition because participants are reporting their own learning about systems and engineering design. The combined results from the retrospective post questions and open-answered questions give insight into the answers to each of the research questions.

To what extent did the students learn fundamental concepts of engineering design?

To answer this research question, 6 retrospective post questions and 2 open-answered questions are analyzed. According to the student responses of the retrospective post questions, they learned fundamental concepts of engineering design throughout the course of the semester. There was a significant difference in the responses to the questions before and after the semester concerning their understanding of engineering design (See Figure 1). The question stem, “I have a deep understanding of engineering design,” resulted in 45% (5 out of 11) of the students changing from a disagree response to an agree response when assessing their knowledge before the semester and their current knowledge. Similarly, the question stem, “I understand the engineering design process,” resulted in 36% (4 out of 11) of the students changing from a disagree response to an agree response when assessing their knowledge before the semester and their current knowledge. The following two question stems, “Without strong math and science skills one cannot contribute to engineering design” and “To add to an engineering design team, I must have a strong background in math, science, and engineering sciences” are similar in content and also result in 5 of 11 students changing from an agree response to a disagree response when assessing their knowledge before the semester and their current knowledge.. The question stem, “I have an understanding of the similarities and differences of engineering science and engineering design,” resulted in 7 students changing from a disagree response to an agree response when assessing their knowledge before the semester and their current knowledge. This was the largest significant difference between before and now responses for the whole survey. This indicates that the students do understand engineering design to some degree after the course of the semester, at the least they do not believe that engineering design is synonymous with engineering science.

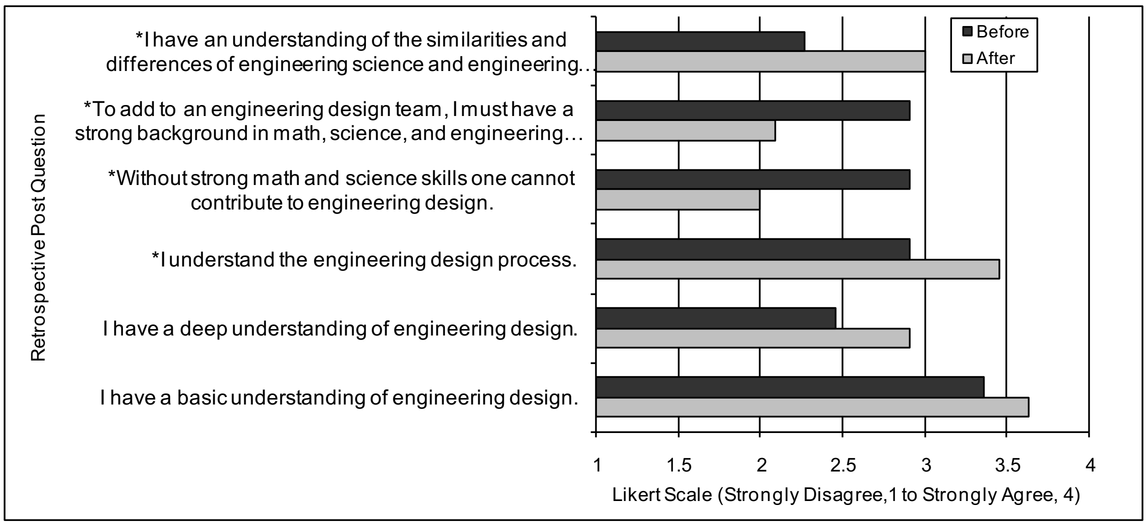

Figure 1. Significant difference and mode of retrospective post questions concerning engineering design

The students’ responses to the questions now, after the course, were tallied and the mode was recorded (See Figure 1). The mode indicated that the students have learned engineering design after the course (according to their responses). The responses are strongly agree (4) or agree (3) for all of the questions where a positive answer indicates that the student understands engineering design. The responses are disagree (2) or strongly disagree (1) for all of the questions where a negative answer indicates that the student has an increased understanding of engineering design.

According to the student responses of the open-answered questions, they have a good understanding of engineering design. The student responses to the question stem, “*Describe the similarities and differences between engineering science and engineering design*” indicated that all of the students have an understanding of engineering design, with one student indicating a low level of understanding according to his response. An example of a typical response to this question is, “Engineering science is steeped in mathematical and scientific principles. Engineering design utilizes some of the core concepts and theories developed in engineering science in its approach to solving problems. Engineering design is a problem solving process that draws on many disciplines, including engineering science, to identify the most appropriate solution." Many of the students mentioned problem solving and processes when describing engineering design and mentioned math and science when describing engineering science.

The student responses to the question stem, *"How has your perception of engineering design changed over the course of this semester?"* were collected and analyzed. A few students, 3 of 11, indicated that there was little to no change in their understanding of the engineering design process throughout the semester. A few students (3 of 11) indicated that they learned that teaching engineering design was not as dependent on math and science as they previously believed. For example, one student explained, "I used to think it was reductionist and limited to math and science. Now I think it is systems primarily with reduction where appropriate using (but not hinging on) math and science." Many of the students (6 of 11) indicated that the systems approach to engineering design was a new aspect of engineering design that they had not previously considered and that this led to a better understanding of engineering design. One student wrote, "I've been enlightened to a new mindset in which I can see the direct applicability of engineering design as it applies to a general education setting in tech ed. We've got something to work with here, something which isn't necessarily about preparing future engineers (although it could do that for some)."

Overall the 6 retrospective post questions and 2 open-answered questions indicated that the students have a strong understanding of engineering design after the course of the semester. Some students mentioned that they had a strong understanding of engineering design prior to the semester, but they did learn a lot about integrating systems thinking into engineering design.

To what extent do the students understand systems thinking and its relationship to engineering design?

To answer this research question, 3 retrospective post questions and 1 open-answered question were analyzed. According to the student responses of the retrospective post questions, they understand systems thinking and its relationship to engineering design after taking the course. There was a significant difference in the responses to the questions before and after the semester concerning their understanding of the systems and reductionist worldview and its relationship to engineering design (See Figure 2). The question stem, "I have an understanding of the systems worldview and its relationship to engineering design.," resulted in 45% (5 out of 11) of the students changing from a disagree response to an agree response when assessing their knowledge before the semester and their current knowledge. Similarly, the question stem, "I have an understanding of the reductionist (Newtonian) worldview and its relationship to engineering design.," resulted in 45% (5 out of 11) of the students changing from a disagree response to an agree response when assessing their knowledge before the semester and their current knowledge. The question stem, "A systems approach to engineering design is inclusive of reductionist methods," resulted in 4 students changing from a disagree response to an agree response over the course of the semester. This indicates that the students understand systems thinking, and that systems thinking includes reductionist thinking, which was a difficult concept for the students to learn first-hand during their projects during the semester.

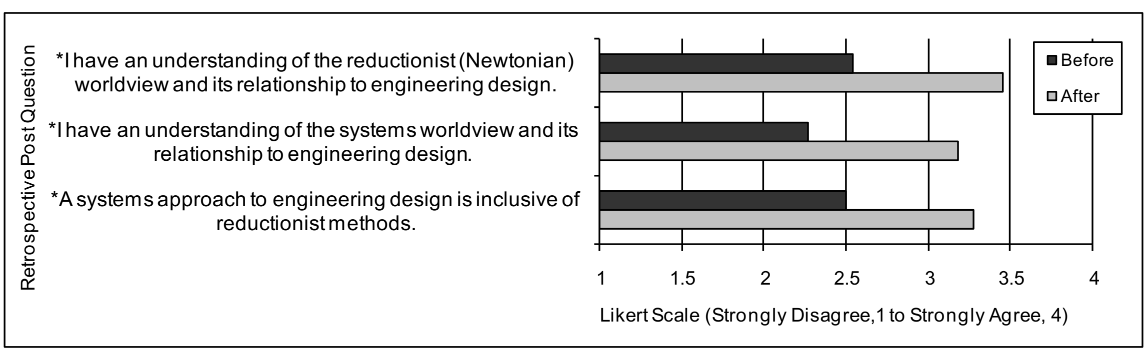

Figure 2. Significant difference and mode of retrospective post questions concerning integrating systems thinking and engineering design

The students' responses to the questions now, after the semester, were tallied and the mode was recorded (See Figure 2). The mode indicated that the students have learned systems thinking and its relationship to engineering design after the semester (according to their responses). The responses are strongly agree (4) or agree (3) for all of the questions. This indicates that the students have a good understanding of systems thinking and its relationship to engineering design.

According to the student responses to the open answered question, *"Describe the systems approach to engineering design,"* the students have an understanding of the systems approach to engineering design. Three patterns emerged when coding this data. The most common response (64%, 7 of 11 students) involved the student discussing the interaction or relationship between parts of the system. This is an important concept to understand in systems thinking and indicates that the students understand this approach to engineering design. An example of a response that was coded as interaction is the following: "The systems approach to engineering design involves observing and studying the dynamic relationships between seemingly unrelated events and/or phenomenon in order to make the best decisions possible that minimize harmful impacts on society, the economy and/or the environment." Another common response to this question was a discussion of a systems approach to engineering design involving a holistic view of the system (55%, 6 of 11 students). Finally, another common response to this question (36%, 4 of 11 students) involved a discussion of moving from a broad perspective to a smaller, detailed perspective. This also indicates that the students understand the systems approach to engineering design, as a systems approach requires that the designer can move between different scales within the hierarchy of the system.

Overall the 3 retrospective questions and 1 open-answered question indicated that the students have a strong understanding of the systems approach to engineering design after the course of the semester. The students indicated that this is the area that they had the largest increase in understanding over the course of the semester.

To what extent do the students believe that the systems approach is an effective way to teach engineering design?

To answer the fourth research question, 7 retrospective post questions and 2 open-answered questions were analyzed. According to the student responses of the retrospective post questions, they believe that a systems approach is an effective way to teach engineering design. There was a significant difference in the responses to a few of the questions before and after the semester (See Figure 3). The question stem, "A strictly reductionist (Newtonian) approach to teaching engineering design would be effective," resulted in 36% (4 out of 11) of the students changing from an agree response to a disagree response when assessing their knowledge before the semester and their current knowledge. Similarly, the question stem, "A strictly reductionist (Newtonian) approach to teaching engineering design to K-12 students would be effective" resulted in 36% (4 out of 11) of the students changing from an agree response to a disagree response when assessing their knowledge before the semester and their current knowledge. This indicates that the students feel more comfortable teaching engineering design after the course of the semester and that they see the shortcomings of using a strictly reductionist approach to teaching engineering design.

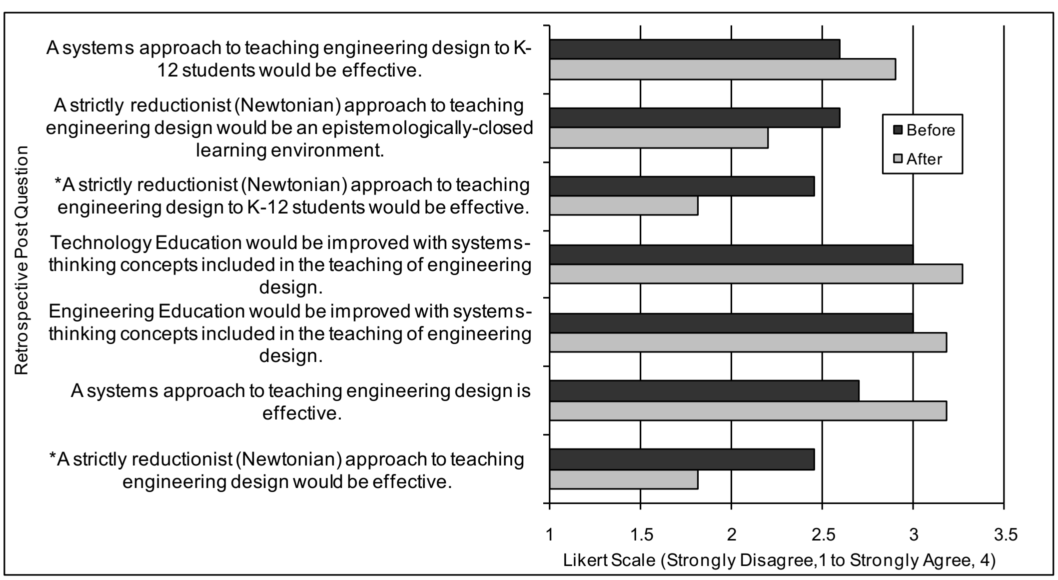

Figure 3. Significant difference and mode of retrospective post questions concerning teaching engineering design

The students' responses to the questions now, after the semester, were tallied and the mode was recorded (See Figure 3). The mode indicated that the students have learned systems thinking and its relationship to engineering design after the semester. The responses are strongly agree (4) or agree (3) for all of the questions where a positive answer indicates that the student feels comfortable teaching engineering design, that a systems approach is an effective way to teach engineering design, and that integrating systems approaches to teaching engineering design will improve engineering and technology education. The responses are disagree (2) for all of the questions where a negative answer indicates that the student understands the limitations of using a strictly reductionist approach to teaching engineering design.

According to the student responses to the open answered questions in this subsection, the students indicated that they believe that the systems approach is an effective way to teach engineering design. The first question, *"In your experience, how effective is a systems-based approach to teaching engineering design? Please explain,"* resulted in 9 of the 11 students indicating that a systems approach to engineering design is an effective way to teach engineering design. Of the 2 that did not indicate that the systems approach was effective, 1 said that they had no experience teaching systems-based approach, and one said that they did not think it was very effective, but their answer indicated that they did not understand the systems approach. A majority (73%, 8 of 11) of the students indicated that the systems approach provided relevancy to the design problem that the reductionist approach would not. This is important as much research in educational pedagogies shows that providing relevancy or context to concepts increases student learning. One student explained that "Students are motivated by relevance and a systems approach (though frustratingly complex at times) has potential to appeal to students. Systems based approach is much more similar to actual challenges graduates will face in their future and inclusive of reductionist tools." In addition to providing relevancy, 6 students indicated that a systems approach to engineering design yields ethically and socially responsible students. This is important for all students, not just students that will pursue an engineering degree. A few of the students (2) mentioned that systems thinking is a difficult concept to understand. They mentioned that this could be detrimental if the objective is to teach engineering design which is already a difficult concept to learn. However, it is important to note that one of these students indicated that they did not understand the systems-based approach according to their response to this question. The responses to the question also showed that an additional student did not understand the systems approach to engineering design. Of the two students that did not understand the systems approach to engineering design, one was the only person in the class with an undergraduate degree in engineering. He also has 8 years experience working as an engineer. Overall, this question indicated that most of the students understand the systems approach to engineering design (9 of 11 or 82%) and that they believe that the strength lies in the relevancy that the systems approach brings to engineering design and in the socially and ethically responsible students that a systems approach to engineering design will yield.

The second question, *"If teaching engineering design to a group of high school technology education students, would you take a systems and/or a reductionist (Newtonian) approach? Please explain,"* indicates again that the students (5 of 11, 45%) believe that a systems approach to engineering design would be most effective because it offers relevancy where the reductionist approach does not. One student explained that "I think that it is important to offer students the context that they will be working in to provide relevance." All of the responses to this question fell into two categories, one is to use both approaches (reductionist and systems) separately and the other is to use both approaches simultaneously. The students (4 of 11, 36%) that mentioned trying both approaches separately suggests that they have some misunderstanding of systems thinking. This is due to the nature of the systems approach which includes the reductionist approach when needed. Most of the students (7 of 11, 64%) indicated that they would use a systems approach to teaching engineering design and that this approach includes reductionism. "Systems thinking embraces reductionism. Thus, to teach systems thinking is to teach reductionism while transcending the confines of it [reductionism]. Systems thinking merely expands on reductionists views and reveals a greater view of the world. Hence, I would use a systems approach to teaching because of the interdisciplinary/cross-curricular nature of systems thinking. By using a systems approach, I could capitalize on areas of overlap between content areas. Hence, making curriculum integration more feasible." The results of this question indicate that 64% of the students have a high level of understanding of the systems approach to engineering design and they believe that it is the most effective way to teach engineering design.

DISCUSSION

The student survey data indicated that after taking the course,

1. The students have a high level of understanding of engineering design,
2. The students feel comfortable teaching engineering design,
3. The students (9 of 11) understand the systems approach to engineering design, and
4. The students plan to use a systems approach to teaching engineering design.

This leads to an answer of the larger research question, *To what extent is it effective to take a systems approach to teaching engineering design to non-engineers?* Overall, the survey results indicate that the systems approach to teaching engineering design to non-engineers is effective. Future empirical research needs to be conducted to determine whether this is an effective approach to teaching engineering design to non-engineers and engineers. Additional questions emerge from this analysis: Are today's practicing engineers uncomfortable with a systems approach to engineering design? Are they concerned only with technical aspects of a design and not the non-linear, complexity inherent in a design (non-technical aspects)? How does this differ for different positions and disciplines within engineering?

Interestingly, the net change in participant responses to the retrospective post questions indicated that the two students with the least amount of net change are the students in the class with prior engineering experience (one has an undergraduate engineering degree).

CONCLUSION

The authors examined how effective it is to teach a systems approach to engineering design. A systems approach to teaching engineering design was taken in the third NCETE course in a series of four courses. The students in the class were NCETE fellows and most (10 of 12) had no experience working as an engineer , and most (11 of 12) have had no formal education (undergraduate degree) in engineering. The participants in this study (11 of 12 students in the class) completed a survey at the end of the semester. The survey consisted of retrospective post questions and open-ended questions. The data suggests that the students learned engineering design deeply enough that they would feel comfortable teaching it, that most of the students had a good understanding of the systems approach to engineering design, and that the students would use a systems approach to teaching engineering design in the future.

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