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Pre-service Science Teachers' Understanding of Science and Engineering Practices, Engineering Design Process, and Scientific Inquiry

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Abstract

This study examined secondary pre-service science teachers' understanding of science and engineering practices, the engineering design process, and the scientific method before and after an intervention. Participants were ten pre-service science teachers. Data were collected through a survey and semi-structured interviews. Results show that after the intervention pre-service science teachers developed an understanding of science and engineering practices and used more engineering-specific language when describing them. They also developed an understanding that both engineering design process and scientific method are cyclical and iterative and that the two processes share many practices, but the biggest difference between them is in their purposes. Pre-service teachers also said that the redesign process in engineering design, and the repetition of steps can occur at any point in engineering design process and scientific method. These findings have implications for science teacher education, and teaching and learning of science and engineering design in schools.

Keywords: Engineering design, Pre-service Teachers, Science and engineering practices, Understanding, Scientific Method

The *Next Generation Science Standards* [NGSS] (NGSS Lead States, 2013) emphasize the integration of engineering design in science instruction. The NGSS define engineering design as, "an iterative cycle of design that offers the greatest potential for applying science knowledge in the classroom and engaging in engineering practices…" (NGSS Lead States, 2013). Although the NGSS accentuate the integration of engineering design in science instruction most science teachers lack the understanding of science and engineering practices (Antink-Meyer & Meyer, 2016), and the engineering design process (Mesutoglu & Baran, 2020; Hynes, 2012) to effectively teach engineering design integrated science (EDIS) lessons to their students. In this paper, EDIS is described as teaching and assessing both engineering design and science core ideas and practices in a lesson. Researchers have attributed this problem to teachers' lack of training in engineering design (e.g. Haag & Megowan, 2015; Fantz et al., 2011; Custer & Daugherty, 2011; Carr & Strobel, 2011;). For example, Haag and Megowan (2015) found that high school science teachers lacked knowledge about engineering design because they never received training in engineering design during teacher preparation. Similarly, Banilower et al. (2018) reported that only 13% of high school teachers, 10% of middle school science teachers, and 3% of elementary school teachers had college coursework in engineering. Yet, the success of engineering design integration in science instruction will largely depend on science teachers' understanding of science and engineering practices, engineering design, and how to integrate engineering design in science lessons. For example, science teachers' superficial understanding of engineering design can lead them to simply relaying the steps of engineering design process to their students, instead of providing detailed explanations of the purpose and rationale for the steps (McCormick, 2004). Thus, there is need to develop science teachers' understanding of the NGSS practices, and engineering design process for them to provide effective EDIS instruction in schools.

Researchers are beginning to take note of this gap in teacher preparation and are investigating ways science teacher preparation programs can best prepare pre-service teachers to integrate engineering in science instruction. However, the research on this topic is still nascent. For example, at the secondary level, few studies (Kim et al, 2018; Mesutoglu & Baran, 2020; and Kitly & Burrow, 2019) have investigated pre-service science teachers' understanding of science and engineering practices. Most studies on engineering design in teacher education have focused on elementary teachers (e.g. Kang, Donovan, & McCarthy, 2018; Duncan, Diefes-dux, & Gentry, 2011). As such, researchers have called for more research on engineering design in secondary science teacher education (e.g. Aminger et al., 2021; Kilty & Burrows, 2019; Carr & Strobel, 2011; Custer & Daugherty, 2009). We also believe that more research on pre-service science teachers' understanding of the NGSS practices, and engineering design is warranted as the findings will contribute to teacher training, and the teaching and learning of science and engineering design in schools. Teachers can effectively infuse engineering design into coursework, if they are familiar and comfortable with the engineering design process.

With these considerations in mind, the purpose of this study was to examine secondary pre-service science teachers' understanding of the NGSS science and engineering practices, as well as their understanding of engineering design process and scientific inquiry before and after an intervention in a science methods course. This study was guided by two research questions, (a) what are secondary pre-service science teachers' understanding of science and engineering practices, engineering design process, and scientific inquiry before and after the intervention? And (b) what are secondary pre-service science teachers understanding of the relationship between engineering design process and scientific inquiry before and after the intervention?

Literature Review

As noted above, research is beginning to emerge on how to develop secondary science teachers' understanding of science and engineering practices, and engineering design process. In the review that follows, we briefly highlight research on the call for engineering design integration in science instruction before turning our attention to science teachers' understanding of engineering design process.

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Inherent in both engineering and science disciplines are the eight science and engineering practices prescribed in the NGSS (NGSS Lead States, 2013) which are: Asking questions (for science) and defining problems (for engineering); Developing and using models; Planning and carrying out investigations; Analyzing and interpreting data; Using mathematics and computational thinking; Constructing explanations (for science) and designing solutions (for engineering); Engaging in argument from evidence; and Obtaining, evaluating, and communicating information. However, researchers contend that there are differences between science and engineering. For example, Cunningham and Carlsen (2014) posited that the *Developing and using models* practice in science assists in explanation and prediction, while engineers use this practice for analysis and evaluation.

Although the NGSS emphasize science and engineering practices in science teaching, studies show that teachers lack understanding of the NGSS practices. For example, Antink-Meyer and Meyer (2016) explored teachers' understanding of science and engineering practices in relation to authentic research and design case studies. They found that teachers' understandings of these practices were plagued by four misconceptions. First, teachers identified outcomes as the driver of the process, rather than the initial research questions. That is, their focus was primarily on how the information would be used to understand the processes in which the scientists or engineers engaged, rather than on the process for generating that information. The second misconception was that science and engineering were part of a hierarchical relationship, in which full realization and maturation of science is only evident when applied through engineering design. The third misconception was that creativity in scientific investigation was inappropriate because creativity was closely tied to subjectivity. Fourth, teachers said the end result of research must be a tangible product or idea, rather than a process. In a similar study, Mesutoglu & Baran (2020) reported that teachers held low understanding of "identifying problem" practice in engineering design process, confirming earlier findings (e.g., Hynes, 2012). However, teachers had a good understanding of the contribution of engineering to the society and the iterative nature of engineering design process. Such gaps in teachers' knowledge of engineering design process can pose a huge challenge in their attempt to integrate it in science instruction. Likewise, Frantz (2011) said science teachers with limited engineering design experience are not likely to integrate certain design elements such as optimization techniques involving mathematical and analytical reasoning in science instruction. Yet, these practices are critical for students to be successful in science learning through engineering design process.

Other studies have reported on teachers' self-reported knowledge of the NGSS practices. For example, Kang et al., (2018) asked teachers to self-report which science and engineering practices they felt most knowledgeable about and confident in teaching them to their students. Teachers reported having the most knowledge and confidence in teaching the following two practices: *Analyzing and interpreting data* and *Asking questions and defining problems*. On the other hand, teachers reported having less knowledge of and confidence in teaching the practices of *Using mathematics and computational thinking* and *engaging in argument from evidence*. In another study, Yasar et al., (2006) surveyed science teachers' perceptions and understanding of design, engineering, and technology (DET). They found that teachers felt that DET was important and should be included in K-12 curriculum. Middle school teachers placed the greatest amount of importance on incorporating DET into the curriculum, followed by high school teachers and then elementary teachers. Despite this, teachers at all levels indicated that they were unfamiliar with DET and did not feel confident in teaching it, though the least experienced teachers felt the most prepared by their preservice teacher training, possibly because of the emphasis of engineering design in recent standards and preservice preparatory programs. Similarly, Hsu et al (2011) reported that while elementary teachers identified DET as an important component of K-12 curriculum, they expressed unfamiliarity with DET and were neutral about their ability to teach it.

Research also shows that teacher professional development (PD) workshops on engineering have enhanced teachers' understanding and perceptions of engineering design. For example, Kilty and Burrows (2019) reported that before the intervention, teachers held novice understanding of engineering and how to teach it. After the intervention they demonstrated a better understanding of engineering design, and their perceptions improved. They attributed teachers' change in their understanding and perceptions of engineering to the explicit instruction on engineering design. Similarly, French and Burrows (2018) reported that the intervention on engineering design in teaching Methods course reinforced preservice teachers' focus on planning lessons which included science and engineering practices.

On the other hand, some researchers have reported that professional development had minimal impact on teachers' conceptions of engineering design. For example, Boesdorfer (2017) engaged high school chemistry teachers in an active one-day PD workshop on the NGSS practices and the engineering design process followed by monthly meetings online, during which the teachers learned more about integrating engineering design into their classrooms and created integrated activities. Prior to the intervention, teachers' conceptions of engineering in the classroom involved simple definitions with "a real-world problem to design for -- and missed the important aspects of engineering design" (p.4). Post-intervention, many teachers still held this belief and struggled with student-centered problem definition. While post-PD teachers did incorporate more NGSS practices into their lesson plans (i.e. developing solutions and carrying out investigations), they struggled to incorporate the iterative nature of the engineering design process.

The NGSS also emphasize on teachers' understanding of scientific inquiry for effective engineering design integrated science teaching in K-12 classrooms (NRC, 2012). However, studies continue to show that teachers do not have sound understanding of scientific inquiry. For example, Barnes et al. (2015) reported that teachers felt that there was an exact or correct scientific inquiry that needed to be followed to collect accurate results. Gauch (2003) also stated that the presentation of scientific inquiry as a set of linear steps, oversimplifies and misconstrues real scientific investigation process. Similarly, Windshitl et al. (2008) argued that the scientific inquiry as it is presented in K-12 science classrooms is a misrepresentation of contemporary scientific practices as it positions experimentation as the only means to generate data, and it focuses on reporting patterns rather than providing explanations.

It is evident in the literature that research on engineering design in secondary science teacher education is still nascent. Literature review also revealed that most science teachers have not received training in engineering design and how to integrate engineering design in science instruction. As such, teachers' misconceptions about the NGSS engineering practices, may be rooted in their lack of exposure to engineering design. Thus, there is a need to provide training to science teachers for them to develop the understanding of engineering design (Kim et al., 2019), and how to integrate it into science instruction (French & Burrows, 2018). In addition to providing opportunities to improve teachers' understanding of science and engineering practices and engineering design, researchers suggest that such professional development programs should also address the similarities and differences between science and engineering (Antink-Meyer & Meyer, 2016; Bybee, 2014).

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Therefore, this study reports secondary pre-service science teachers' understanding of science and engineering practices, the engineering design process, and the scientific inquiry before and after an intervention.

Methodology

Design and Participants

One group pre-posttest design was employed in this study. Participants were seventeen pre-service science teachers enrolled in a secondary science teacher education program at a research university. Participants were ten female and seven male pre-service teachers from the post-graduate Master of Teaching (PGMT) program and the Bachelor of Arts and Master of Teaching (BMT) program. Specifically, 13 pre-service teachers (4 in Chemistry, 5 in Biology, 2 in Physics, and 2 in Earth Sciences) were in the PGMT while the remaining four were in BMT. The age range for PGMTs was 24-29 years while the age range for BMT was 22-25 years. The PGMT pre-service teachers enrolled in the program after earning their bachelor's degrees prior to pursuing the MT degree. Fourth year BMT pre-service and first year PGMT students take the same courses over a 2- year period in our science teacher education program. Upon completion of the program both BMT and PGMT pre-service teachers receive a Masters in Teaching (MT) degree, and a science teaching license for grades 6–12. We have used pseudonyms of the participants throughout this paper. None of the participants had formal K-12 science teaching experience. Additionally, none of them had experienced NGSS in high school because NGSS were published and implemented after they had all entered college. However, three PGMTs had degrees in engineering and worked in industries before enrolling in our program.

Intervention

Before the intervention on engineering design integrated science teaching in science methods course, participant pre-service teachers took courses that addressed the following topics: educational contexts; adolescents' learning and development; integration of language and literacy in content areas; special education; learning theories; and history of science. They also took a science method course that covered the nature of science, and active-learning instructional strategies (e.g., inquiry, problem- and project-based learning, engineering design integrated science, argumentation, case-based learning, and the Predict-Observe-Explain and 5E models of instruction). For each instructional method, pre-service teachers participated in a lesson taught by the instructor modeling the instructional method, and then designed lesson plans, activities, or units exemplifying the instructional method. The intervention on the NGSS practices, engineering design, scientific inquiry, and how to integrate engineering design in science teaching was done in a second science methods course in two spring semesters. In each semester, the intervention took six weeks. Four instructors led the intervention: Two engineering professors, one engineering education professor, and one science education professor. The intervention was designed for pre-service science teachers to: Become familiar with the *New Framework for K-12 Science Education* (NRC, 2012) and the NGSS (NGSS Lead States, 2013); Learn how to read the NGSS; Understand and apply disciplinary core ideas, cross-cutting concepts, and science and engineering practices; Understand and apply engineering design process; Develop understanding of similarities and differences between engineering design and scientific inquiry; Develop engineering design integrated science (EDIS) units and activities; Develop teacher guide manuals for EDIS instruction; and Create a collection of EDIS teaching and learning resources.

Instructional Model and activities. We adopted the informed engineering design framework (Chiu et al., 2013) to guide our instruction during the intervention (See Fig. 1). The framework is designed to help make engineering design processes explicit for teachers or students. Additionally, the informed engineering design framework guides learners to develop engineering design skills and science concepts through inquiry.

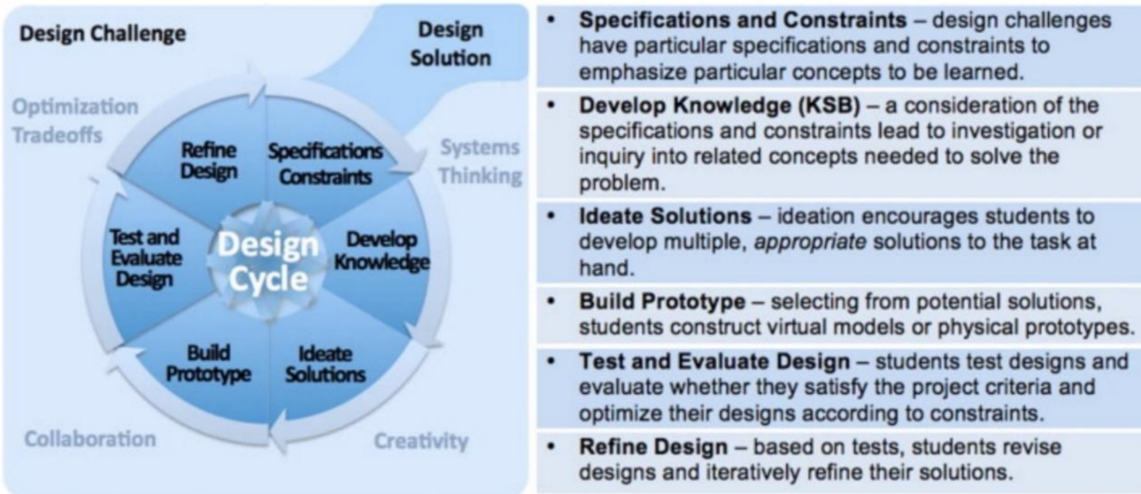

Figure 1: Informed Engineering Design Instructional Model. (Chiu et al.,2013)

The Intervention objectives were achieved through individual and group activities, and EDIS instructional materials development. First, pre-service teachers learned about the principles of engineering, the role of engineering in society, prominent engineers in the US. Second, pre-service teachers participated in an activity where they were challenged to build a solar-powered car using the materials (see Schnittka & Richards, 2016) that were provided. Pre-service teachers defined the challenge, developed knowledge, redefined the problem, ideated solutions, built prototypes, tested and evaluated the prototypes, and revised their prototypes. Pre-service teachers then presented their cars, the design process, energy transformation processes, and their reflections on the design process to the class. In this activity, pre-service teachers learned about solar energy, engineering design process, and NGSS practices by responding to the design challenge.

Third, pre-service teachers learned about the similarities and differences between scientific inquiry and engineering design process through activities that illustrated both processes. Specific examples were provided during the discussion. For example, during the solar-powered car activity pre-service teachers were asked to identify the NGSS practices that applied to engineering design process and scientific inquiry, and both.

Fourth, pre-service teachers were involved in analyzing commercially prepared engineering design integrated science activities for representation of engineering design process and science and engineering practices prescribed in the NGSS. The goal for this activity was for pre-service teachers to learn how to identify science and engineering practices in activities prepared by others before they started developing their own activities.

Fifth, pre-service teachers were engaged in characterizing engineering design integrated science activities from online sources (e.g.TeachEngineering- https://www.teachengineering.org/) for the nature of integration using a continuum model which identifies activities into five categories: *Independent engineering design; Engineering focused; Balanced engineering design and science; Science focused; and Independent Science* (Mumba & Ochs, 2018). The goal of this

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activity was for pre-service teachers to gain the skill for determining the nature and extent to which engineering design and science are integrated in commercially prepared activities.

Sixth, participating pre-service teachers completed a resource collection assignment that was developed for pre-service teachers to create engineering design resources they you would use to teach engineering design integrated science in their classrooms. For each resource, the preservice teachers were asked to provide the following information, title, science concepts/topics the engineering design resource would address; brief description of how the resource would be used to teach science concepts and engineering design in science classrooms; science and engineering practices, disciplinary core ideas, and crosscutting concepts the resource is addressing; modification(s) they would make for the engineering design resource to effectively address the identified science concepts.

Seventh, each pre-service teacher created a teacher guide manual, and EDIS units. The creation of these artifacts demonstrated their knowledge of the engineering design process and skills for developing EDIS curriculum materials. Throughout the intervention, pre-service teachers frequently presented their work and discussed their EDIS units in groups to receive feedback, and thus reinforcing the iterative design process.

Below are summaries of additional example EDIS activities that were implemented in our intervention.

Slime mold quarantine. This engineering design integrated biology activity is designed to engage learners in engineering design process, while learning about the characteristics of slime mold (Holder et al., 2019). Additional goals of the activity are for students to: (a) to apply the steps of the engineering design process, (b) Understand that the engineering design process is fluid and iterative, (c) Understand that questions posed in science can be solved with solutions designed through engineering design, (d) Identify aspects of the slime mold quarantine lab as steps of the engineering design process, (e) Make observations to determine if they were successful and then use this data to make design revisions, and (f) Communicate their findings using scientific and engineering language.

Energy-plus home design challenge. Pre-service teachers were engaged in designing energy efficient home using the simulation created by Concord consortium (https://concord.org/newsletter/2015-fall/designing-energy-plus-home/). The Energy3D activity is designed to engage learners in the NGSS science and engineering practices. The integrated capability of concurrent design, simulation, and analysis within Energy3D enables participants to test and evaluate multiple design ideas through virtual experimentation. Pre-service teachers were tasked with designing an energy-efficient house that, over the course of a year, produces more renewable energy than the energy needed for heating and cooling. Pre-service teachers were also expected to meet a set of design criteria and constraints. For example, the house should have one of these specified architectural styles: the size cannot be too big or too small, and the cost must not exceed the budget. The activity enabled teachers (a) to apply engineering design process and learn more about energy concepts, (b) simulate situations that are not possible to create in a lab (e.g. waiting for very long time to collect data on energy use in a real house), and (c) to experience low-cost alternatives to expensive experiments.

Teaching Osmosis through engineering design. This engineering design integrated biology activity that is designed to engage learners in learning about osmosis through engineering design process (Rice et al., 2022) This unit encouraged pre-service teachers to apply their own scientific understanding and engineering design skills to solve problems. Prior to the start of the unit, teachers were introduced to the engineering design process. Pre-service teachers learned that the engineering design process is both iterative and flexible. The unit is designed so that learners would achieve the following learning objectives: (a) understand the properties of the cell membrane; (b) understand types of cellular transport -- specifically osmosis; (c) learn about isotonic, hypertonic and hypotonic solutions; (d) learn and apply the engineering design process to solve a problem; (e) understand that engineering design is a process that involves redesigning the solution; and (f) demonstrate engineering design skills.

Scientific inquiry and engineering design process. Pre-service teachers learned how the engineering design process is similar to, but different from the scientific inquiry, as this is an area that is essential for teachers to understand for effective integration of engineering design and science in science classrooms. Similarities between the two processes emphasized during the intervention include: the cyclical (iterative) nature; the identification of a problem or question; the need for background research; the need to make observations; the need to conduct a test; data collection; and the need to communicate findings. When highlighting the differences between the two processes, central to the conversation was the fundamentally different purpose of each process: engineering design is used to create solutions for real-world problems and the scientific inquiry is used to discover information about the natural world. Table 1 shows additional differences between engineering design and scientific inquiry addressed in the intervention.

Table 1.
Differences between Engineering Design Process and Scientific Inquiry

Engineering Design Process	**Scientific Inquiry**
Purpose: Designing solutions for real world problems.	Purpose: Discovering information about the natural world
Creates a new thing	Creates new knowledge through describing existing things
Success = positive impact on people/society	Success = gaining new knowledge
Background research includes people.	Background research mainly scientific literature
Addresses needs of people	Addresses an investigative question
Works with the **artificial** world.	Works with the **natural** world
Frequently considers many ideas	Frequently considers only a single hypothesis once conducting experiment
Prototypes used to learn how to better meet people's needs (and to uncover those needs)	Experiments used to address an investigative question.
Work reviewed by consumers/users	Work reviewed by peers
At any point in time, lots of good solutions	At any point in time, only one best answer.

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Data Sources

Data was collected using a questionnaire and semi-structured interviews. This questionnaire has six main open-ended items designed to assess pre-service teachers' understanding of the NGSS science and engineering practices, engineering design process, and the scientific inquiry (see Appendix A). The questionnaire was developed by the researchers. The items are aligned with the concepts that were addressed in the intervention. After developing the questionnaire, it was evaluated for content validity by two experts, one in science education and the other one in engineering education. The questionnaire was revised based on the feedback from the experts. Then, the questionnaire was administered to four students, who were not part of the study, to establish if the items were clear to respondents. We revised the questionnaire items using the feedback from the four students. The participant pre-service teachers completed the questionnaire before and after the intervention. First, pre-service teachers were asked to describe the following terms: engineering, engineering design process, design challenge in engineering, and design solution in engineering. Second, the pre-service teachers were asked to explain the similarities and differences between the scientific inquiry and the engineering design process. Third, pre-service teachers were asked to describe each of the eight NGSS science and engineering practices.

Following the intervention, the pre-service teachers were interviewed using a semi-structured interview protocol (see Appendix B). All interviews were audiotaped and transcribed. Each interview was 30 minutes long. Pre-service teachers were asked to explain the meaning of the eight science and engineering practices. Pre-service teachers were asked to draw and explain their conceptions of the engineering design process and the scientific inquiry. Participants were also asked to describe the similarities and differences between engineering design process and scientific inquiry.

Data Analysis

We used the inductive method as described by Thomas (2006) to analyze both the questionnaire responses and interview data. The questionnaire analysis occurred in two phases. In the first phase, two researchers independently reviewed preservice teachers' pre- and post-intervention responses, identifying emerging themes across participants' responses for each question. Following independent analysis, researchers met to discuss their findings. Any similarities in themes were retained for further review, and excerpts were identified that exemplified the theme across responses. Where differences existed, the researchers went back to the questionnaire responses to come to a consensus. In the second phase, the emerging themes were grouped into main themes. For example, all themes on science and engineering practices were combined. By doing so, we were able to look at more global themes regarding preservice teachers' understanding of the NGSS practices, engineering design, and scientific inquiry before and after the intervention. Interview transcripts were analyzed using the same two-phase procedure outlined above. Following analysis, interview themes were compared with those from the questionnaires to identify main themes across both data sources.

Findings

Data analysis revealed the following four main themes (a) increased use of engineering-specific language among pre-service teachers when describing the NGSS practices; (b) increased understanding of the NGSS science and engineering practices among pre-service teachers; (c) pre-service teachers' understanding of both the engineering design process and scientific inquiry as cyclical and iterative processes, and that they have different purposes; and (d) pre-service teachers said the redesign process in engineering design, and the repetition of steps can occur at any point in engineering design process and scientific inquiry. We present each theme in turn, below. Example excerpts have been provided to exemplify each theme.

Teachers' increased use of engineering-specific language

Before the intervention, pre-service teachers' descriptions of the NGSS science and engineering practices were mainly situated in a scientific domain. After the intervention, there was increased use of engineering design-specific language among teachers when describing the NGSS practices. For example, when asked to describe the practice of *developing and using models*, words such as creation, representation, and explanation were used with consistent frequency across the pre and post intervention responses. However, after the intervention pre-service teachers used more engineering design terms, (e.g., prototype, design challenge, and design solutions) in describing the NGSS practices. Prior to the intervention, no participant pre-service teacher mentioned prototype in survey responses, while most post-intervention responses included the word prototype. For example, prior to instruction Sam described the "*developing and using models*" practice as "finding a tangible resource to understand a science concept," whereas after the intervention, he described the same practice as "creating prototypes in form of physical or digital models to solve the problem."

Similarly, prior to the intervention, pre-service teachers' understanding of *planning and carrying out investigations* practice was largely situated in a scientific inquiry-like procedure, in which scientists develop and implement a procedure to collect data and draw conclusions. After the intervention, most participants used engineering design specific language, (e.g. discussion of constraints, solving problems, and using prototypes), in addition to science-specific language. For example, prior to the intervention, Jena described the *planning and carrying out investigation*s practice as "coming up with an inquiry that will test a hypothesis under a specific set of conditions." Following the intervention, she described the same practice as follows:

> "…to plan an investigation, you have to think through the problem and come up with all the parameters, and constraints you will need to work within, then develop a procedure for running it. To carry out the investigation, you follow your procedure, collect data, analyze, redesigning or explaining failures when necessary"

The post-intervention emergence of engineering design language was also evident in preservice teachers' descriptions of the *analyzing and interpreting data* practice. Before the intervention, no participant pre-service teacher included engineering design language in the description of this practice.

Teachers' understanding of science and engineering practices

In addition to the increased use of engineering design language displayed by the pre-service teachers, they also demonstrated understanding of the NGSS science and engineering practices following the intervention. For example, prior to the intervention the *using mathematics and computational thinking* practice was largely conceptualized as something that only occurs during data analysis to help researchers understand results. After the intervention, pre-service teachers identified additional application of *mathematical and computational thinking* practice in science and engineering, including the validity of the data collection process, expressing a concept or postulate inform of a formula, making predictions, creating mathematical or computational models, and representing data, relationships between variables, and design solutions. The expanded understanding of this practice among pre-service teachers is evident in the following interview excerpt:

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"Originally, I thought that it was like literal math…and I guess in a way you do use a lot of math, but I think that it's more focused on both math and computational thinking. So, can you break this problem down into smaller parts to look at it? Can you take this problem apart and identify what the constraints are for the best solution? You represent the main concept in a formula or model" (Anita)

Pre-service teachers also developed an understanding of the O*btain, evaluate, and communicate information* practice. Prior to the intervention, none of the participant pre-service teachers attempted to describe "evaluate" information in science and engineering. After the intervention pre-service teachers were able to explain the *Obtain, evaluate, and communicate information* practice very well. For example, Selena said, "Obtaining is gathering background or contextual information or results. Evaluating is judging what information is relevant or useful for a particular argument or position. Communicating information is presenting what you know in clear and concise dictation".

Teachers' Understanding of Engineering Design Process

To assess pre-service teachers' understanding of the engineering design process (EDP), we asked them to describe the EDP both in the survey and interviews. Prior to the intervention, pre-service teachers viewed engineering design as a process engineers used to solve a problem. However, participants did not provide details on the type of problems engineers solve using engineering design process. For example, Jackson said "It is inquiry in which to test a problem and discover the solution". None of the participants said the engineering design process is used by engineers to solve real-world human problems. Other participants described engineering design from a classroom instructional perspective. For example, Katie wrote "engineering design process is where students are presented with a problem, and they have to design a solution for it. In the process, they learn about the concepts". Some participants provided more of a definitional response. For example, Victoria described the engineering design process as, "the application of science and technology in building something". Additionally, most pre-service teachers tended to conceptualize the engineering design process primarily as building to the exclusion of other components of the process, such as gathering background information, testing, redesign or communicating the findings. Although pre-service teachers listed at least two steps of the engineering design process before the intervention engineering design steps were vaguely listed and uncoordinated, and mostly reflective of the steps of the scientific inquiry. Furthermore, most pre-service teachers viewed engineering design as a rigid linear process before instruction.

After the intervention, pre-service teachers provided detailed descriptions of the engineering design process. While words such as building, and designing were still prevalent, they were now situated within a multi-step engineering design process, which included the NGSS practices. For example, Sharon provided the following description of the engineering design process:

> "Engineering design process can start by identifying a problem and following up with background research to get the full extent of the issue at hand. Then, engineers brainstorm a multitude of ideas for solving the problem and select the best or combination of best ideas to build a prototype out of. The Prototype is then run through tests which will assess the effectiveness of the solution in solving the problem. Usually, following testing engineers redesign their prototypes that it better meet the problems and specifications. However, redesigning can occur at any point in time during the engineering design process. Engineer's then share their process and product often in the form of a presentation or portfolio"

As shown in the excerpt above, Sharon included choosing the best solution, analyzing data, communicating findings, and justifying the design solution in her description of the engineering design process. Similarly, following the intervention, there was more reference to the cyclical and iterative nature of the engineering design process among pre-service teachers. Participant teachers subscribed to the importance of redesign, and the need to optimize solutions in engineering. For example, Jim provided the following response in the interviews:

> “Before I didn't really know too much about engineering design. I thought it was . . . more linear process. Once you've found your solution to the problem, that's it. Whereas now, after having learned it, spent the semester talking about it, it's more circular in nature where you're constantly refining, and I guess it can really be applied to just about anything”

Pre-service teachers also acknowledged that the redesign process and the repetition of steps can occur at any point in the engineering design process. For example, in concluding his description of the engineering design process Jackson said, “…. Everywhere throughout this process there is a potential to redesign and refine the solution.” Figure 2 shows the EDP diagram Jackson drew during the interviews. He viewed EDP as a cyclical process with redesign and refining as a separate entity that could occur at any time.

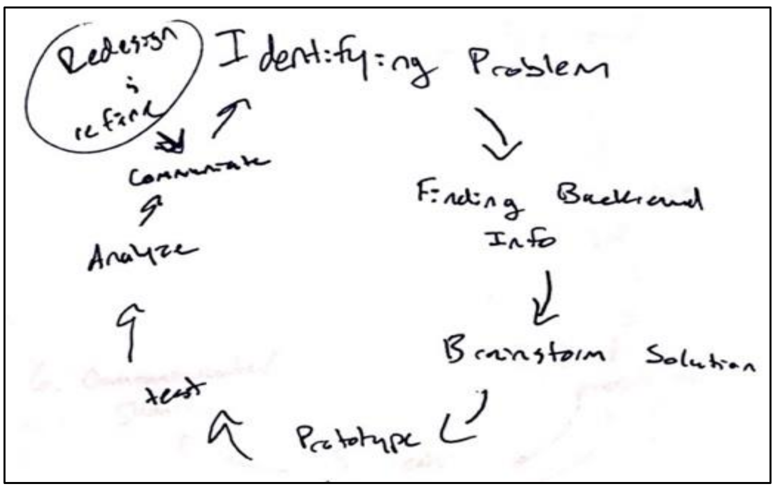

Figure 2. Jackson’s illustration of the EDP after intervention

After the intervention, pre-service teachers also indicated that one can start a design problem or challenge from any step in the engineering design cycle. Furthermore, pre-service science teachers acknowledged that there are other engineering design processes beyond the one described in the intervention.

Prior to the intervention, preservice teachers focused on the creation of only one design solution. Following the intervention, participants mentioned that one can suggest several design solutions and choose the best solution to develop a prototype. For example, during the interviews Andrea said:

> “First, engineers identify the problem or challenge. Then, they do research to develop their background knowledge. From there, they come up with multiple solutions that they can narrow down to one best (for now) solution. They will create their prototype, test their prototype, and present their results”

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Additionally, after the intervention participant teachers used more engineering design specific language (e.g., prototype, constraints, optimization, challenges, and design solutions) in describing engineering design. Pre-service science teachers also acknowledged that building and testing a prototype is an important element of the engineering design process.

Teachers' understanding of the Scientific Inquiry & Engineering Design process

Pre-service teachers were asked to describe the scientific inquiry before and after the intervention. Before the intervention most participants viewed scientific inquiry as a linear process. For example, Selena wrote "Scientific inquiry is a linear process that involves conducting experiment, data collection, and analysis". After the intervention, most teachers provided detailed descriptions of the scientific inquiry and referenced the following steps: Formulating question; developing a hypothesis; performing background research; designing an experiment; testing the hypothesis through experimentation; analyzing the data; and communicating the results. Pre-service teachers also said that the scientific inquiry deals with the natural world. For example, Katie wrote that "scientific inquiry is a process of understanding the world around us (nature, environment, interactions) and developing knowledge". Additionally, in the interviews most participants said the scientific inquiry was cyclical in nature.

Participant teachers were also asked to describe the similarities and differences between the engineering design and scientific inquiry. Before the intervention, pre-service science teachers mainly focused on the differences between the two processes. Most responses lacked detailed information to distinguish the scientific inquiry and the engineering design process. For example, Jackson said "Scientific inquiry is more focused on asking questions and then doing trials to see if you were asking the right question. Engineering design process is more about starting with a question and working to find the answer or solution.". After the intervention, pre-service teachers were explicit on the similarities and differences between scientific inquiry and engineering design process. Most teachers referenced specific steps as common between the two processes. For example, conducting background research, designing and/or implementing a test, and communicating results were the most mentioned common steps between the scientific inquiry and the Engineering design process. They also viewed both processes as cyclical and iterative. For example, Figure 3 shows Sharon's drawings of the engineering design and the scientific inquiry during the interviews.

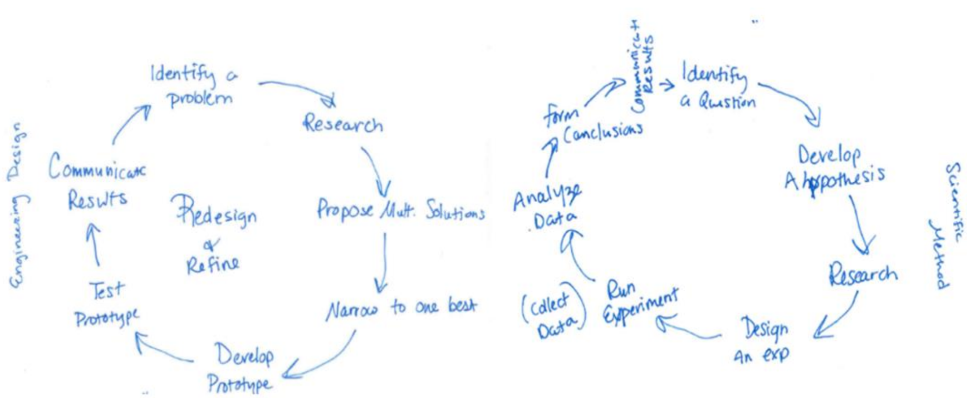

Figure 3: Post intervention Sharon's view of the engineering design and the scientific inquiry

When considering the differences between the two processes, pre-service science teachers cited the purpose of each process as a hallmark difference between them. Most preservice teachers viewed scientific inquiry as a process for answering questions or providing explanations and the EDP as focused on solving human problems. For example, Anita shared:

> "Scientific inquiry attempts to answer a question while the engineering design process attempts to solve a problem. Scientific inquiry deals with the study of the natural world around us, while the Engineering Design process deals with the creation of an artificial world to solve real world problems"

Similarly, after the intervention, most pre-service science teachers stated that the scientific inquiry deals with the natural world, while the EDP addresses the artificial world. For example, Jim said "Scientific inquiry involves discovering the natural world by asking questions. Engineering design involves identifying a real world or human problem and developing a solution to fix the problem."

Discussion

Results show that after the intervention participant pre-service teachers developed understanding of science and engineering practices, engineering design process, and scientific inquiry. They also increased the use of engineering design-specific language when describing practices. These results are in keeping with those reported by Kilty and Burrows (2019). On the other hand, our findings are in contrast with those reported by other studies. For example, Boesdorfer (2017) reported that after the PD, many chemistry teachers still held low understanding of science and engineering practices. Similarly, in an exploratory study, Antink-Meyer and Meyer (2016) reported that teachers' understanding of science and engineering practices were plagued by misconceptions. Kang et al. (2018) also found that most teachers reported lack of knowledge in the NGSS practices such as *Using mathematics and computational thinking* and *engaging in argument from evidence*. Yasar et al. (2006) and Hsu et al. (2011) posited that teachers indicated unfamiliarity with design, engineering and technology and they did not feel confident in teaching them.

Participant pre-service teachers' understanding of the engineering design process is also in contrast with the results in previous studies. For example, Hynes (2012) reported that even after the intervention most middle school science teachers displayed inconsistent level of understanding of the engineering design process, as most of them demonstrated more knowledge for the "construct a prototype" and "redesign" than other steps. Researchers have attributed teachers' misconceptions about the engineering design process to lack of exposure to engineering (e.g., Banilower et al., 2018; Haag and Megowan (2015). For example, Haag and Megowan (2015) reported that high school teachers lacked knowledge about engineering design because they never received instruction in engineering during teacher training. In our study, we provided training in engineering design to participant pre-service teachers through several EDIS activities designed to enhance teachers' understanding of engineering design, and how to integrate engineering design in science teaching.

Another major finding in this study was the pre-service teachers' understanding of the cyclical and iterative nature of both the engineering design process and scientific inquiry after the intervention. Participant pre-service teachers also acknowledged that there was more than one version of engineering design process, and scientific inquiry but they all serve the intended purposes in their disciplines. Similarly, Mesutoglu & Baran (2020) reported that after the

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intervention, teachers developed understanding of the iterative nature of engineering design process. However, this finding is not in keeping with the results reported in earlier studies. For example, Hynes (2012) found that middle school teachers did not have a good understanding of the cyclical nature of the engineering design process. Similarly, Barnes and Angle (2015) reported that many science teachers said there was one exact or correct scientific inquiry that needed to be followed to collect accurate results. Antink-Meyer and Meyer (2016) also reported that teachers mainly considered scientific knowledge as the foundation of engineering and ignored the commonalities between the two disciplines. Our participant pre-service teachers understanding of the cyclical nature of engineering and scientific inquiry can be attributed to two reasons: First, throughout the intervention both scientific inquiry and engineering design process were taught as cyclical processes; and the pre-service teachers were involved in developing EDIS instructional materials to address both scientific inquiry and engineering design processes. Thus, we believe that through engaging in and developing EDIS units and activities, most pre-service teachers came to understand the cyclical and iterative nature of both engineering design and scientific inquiry. We also suggest that science teacher education programs should emphasize that teachers' understanding of the differences and similarities between engineering design and scientific inquiry is essential for effective EDIS instruction, and that focusing on only one of them misses the opportunity to provide a complete understanding of both processes among teachers and their students.

Overall, our study shows that the intervention positively impacted on the pre-service science teachers' understanding of science and engineering practices, engineering design and scientific inquiry. The following possible explanations for our results merit consideration. First, we believe the collaboration of two engineers, an engineering educator, and a science educator played a significant role in the success of the intervention. Engineers came into the intervention with practical experience in developing engineering education curriculum materials and working with in-service teachers. Some of the activities pre-service teachers did in the intervention were created by the two engineers and one engineer educator. The science education expert provided pedagogical strategies for integrating engineering in science teaching. This collaboration of engineers, engineering educator, and science educator in preparing pre-service teachers in engineering is rare. Many studies on engineering in teacher education have reported collaborations between science educators (Capobianco et al., 2020; French & Burrows, 2018) or between science and mathematics faculty members (e.g., Nesmith & Cooper, 2021). Second participants may have been motivated to learn more about engineering design because current science education reforms require them to incorporate it in science instruction. The presence of the three pre-service teachers who had degrees in engineering played a role in this intervention. During the activities we observed the three participants taking leading role in group engineering design activities and explaining design elements to other members of the group. We also observed preservice teachers who had scientific research experience explaining scientific inquiry process to their members of the group. Some of our pre-service teachers were career changers. They had worked as scientists or engineers in industries. As such, we believe these variables contributed to participant pre-service teachers understanding of practices, engineering design and scientific inquiry. Third, participant pre-service teachers were immersed in authentic EDIS activities that explicitly addressed the NGSS practices, engineering design process, and scientific inquiry. Therefore, it is possible to assume that pre-service teachers' experiences with such EDIS activities enabled them to learn more about the NGSS practices, engineering design process and scientific inquiry. Fourth, pre-service teachers were engaged in developing EDIS units and activities, and teacher guide manuals. They were required to demonstrate how the appropriate NGSS dimensions (core ideas of science and engineering design, practices, and crosscutting concepts) were addressed in their units. In the teacher guide manuals, pre-service teachers were required to describe engineering design process and provide clear directions that other teachers can follow to develop their own EDIS instructional materials. Through these tasks, participant teachers were directly engaged in learning and applying the NGSS science and engineering practices, engineering design process, and scientific inquiry.

The growth demonstrated by pre-service teachers in their understanding of the NGSS practices, and engineering design, and their increased use of engineering specific language when describing the practices have implications for science teacher education. For example, preservice teachers' low conceptual knowledge of engineering design reported in our pre-intervention results and in previous studies should be a call to action in science teacher education. Science teacher education programs should refocus their science methods courses to explicitly address engineering design to ensure that pre-service science teachers are adequately prepared to teach science and engineering design as prescribed in the NGSS. We believe an implicit instructional approach to engineering design in science teacher education is likely to limit the opportunity for teachers to develop a deeper understanding of the engineering design process and how to integrate it in science instruction. Likewise, an implicit EDIS instructional approach is unlikely to have positive impact on students' understanding of engineering design and science core ideas outlined in the NGSS.

Recommendations for Future Research

Although the findings in this study cannot be generalized due to a small number of participants, our findings suggest the evidence to support the need for professional development on engineering design for secondary pre-service science teachers to develop the understanding of engineering design process and how to integrate it in science instruction. We also suggest three areas for future research on engineering design in science teacher education: First, extend this study to a large sample of participant secondary pre-service science teachers. Second, investigate the relationship between teachers' understanding of engineering design integrated science teaching and their instructional practices in science classrooms. Third, examine the extent to which teachers' understanding of the NGSS practices and engineering design process impact their students' understanding of science concepts and engineering design process. These studies would provide evidence on whether teachers' understanding of engineering design is related to their EDIS instruction and students' achievement in science and engineering design.

Conclusions

Our results show that participant pre-service teachers developed an understanding of the NGSS science and engineering practices, the engineering design process, and the scientific inquiry after the intervention. These results suggest that explicit instruction on engineering design process and scientific inquiry through intensive PD activities and EDIS instructional materials development can enhance pre-service science teachers' understanding of the NGSS practices, as well as their understanding of engineering design, scientific inquiry, and the cyclical and iterative nature of both processes.

References

Aminger, W., Hough, S., Roberts, S. A., Meier, V., Spina, A. D., Pajela, H. & Bianchini, J. A. (2021). Preservice secondary science teachers' implementation of an NGSS practice: Using mathematics and computational thinking. *Journal of Science Teacher Education*, *32*(2), 188-209.

https://ir.library.illinoisstate.edu/jste/vol58/iss1/5
DOI: 10.61403/2158-6594.1500

Antink-Meyer, A., & Meyer, D. Z. (2016). Science teachers' misconceptions in science and engineering distinctions: Reflections on modern research examples. *Journal of Science Teacher Education*, *27*(6), 625-647.

Banilower, E. R., Smith, P. S., Malzahn, K. A., Plumley, C. L., Gordon, E. M., & Hayes, M. L. (2018). Report of the 2018 NSSME+. *Horizon Research, Inc.*

Barnes, C., Angle, J., & Montgomery, D. (2015). Teachers describe epistemologies of science instruction through methodology. *School Science and Mathematics*, *115*(3), 141-150.

Boesdorfer, S. B. (2017, June). *High school chemistry teachers' views of engineering inclusion before and after a professional development program* (Center for Educational Transformation Research Brief No. 2). Retrieved from https://cet.uni.edu/sites/default/files/boesdorfer_brief_0.pdf

Burghardt, M. D. & Hacker, M. (2004). Informed Design: A contemporary approach to design pedagogy as the core process in technology. *Technology Teacher, 64*, (1). 6.

Bybee, R. W. (2014). NGSS and the next generation of science teachers. *Journal of Science Teacher Education, 25*(2), 211-221.

Carr, R., & Strobel, J. (2011). Integrating engineering into secondary math and science curriculum: Preparing teachers. *1st Integrated STEM Education Conference*. Ewing, NJ: IEEE.

Chiu, J. L., Hecht, D., Malcolm, P., DeJaegher, C., Pan, E. Bradley, M., & Burghardt, M. D. (2013). WISEngineering: Supporting Precollege Engineering Design and Mathematical Understanding. *Computers & Education*, 67, 142-155.

Capobianco, B. M., Radloff, J., & Lehman, J. D. (2020). Elementary science teachers' sense-making with learning to implement engineering design and its impact on students' science achievement. *Journal of Science Teacher Education, 32*(1), 39–61.

Cunningham, C. M., & Carlsen, W. S. (2014). Teaching Engineering Practices. *Journal of Science Teacher Education, 25*(2), 197–210.

Custer, R. L. & Daugherty, J. L. (2009). Professional Development for Teachers of Engineering: Research and Related Activities. *The Bridge: Linking Engineering and Society, 39*(3),18-24.

Custer, R.L. & Daugherty, J.L. (2011) Teaching engineering concepts in high school project. *Journal of Technology Education, 23*(1), 2-4.

Duncan, D., Diefes-dux, H., & Gentry, M. (2011). Professional development through engineering academies: An examination of elementary teachers' recognition and understanding of engineering. *Journal of Engineering Education, 100*(3), 520-539.

Fantz, T. D., De Miranda, M. A., & Siller, T. J. (2011). Knowing what engineering and technology teachers need to know: an analysis of pre-service teachers engineering design problems. *International Journal of Technology and Design Education*, *21*(3), 307-320.

French, D. A., & Burrows, A. C. (2018). Evidence of science and engineering practices in preservice secondary science teachers' instructional planning. *Journal of Science Education and Technology*, *27*(6), 536-549.

Gauch, H. G. (2003). *Scientific inquiry in practice*. Cambridge University Press.

Haag, S., & Megowan, C. (2015). Next generation science standards: A national Mixed-methods study on teacher readiness. *School Science and Mathematics, 115*(8), 416-426.

Holder, T., Pottmeyer, L., & Mumba, F. (2019). Slime Mold Quarantine: An Engineering-Design-Integrated Biology Unit. *The American Biology Teacher, 81*(8), 570-576.

Hsu, M. C., Purzer, S., & Cardella, M. E. (2011). Elementary teachers' views about teaching design, engineering, and technology. *Journal of Pre-College Engineering Education Research*, 1(2), 5.

Hynes, M. M. (2012). Middle-school teachers' understanding and teaching of the engineering design process: A look at subject matter and pedagogical content knowledge. *International Journal of Technology and Design Education, 22*(3), 345-360.

Kang, E., Donovan, C., & McCarthy, M. (2018). Exploring Elementary Teachers' Pedagogical Content Knowledge and Confidence in Implementing the NGSS Science and Engineering Practices. *Journal of Science Teacher Education, 29*:1, 9-29.

Kilty, T. J., & Burrows, A. C. (2019). Secondary science preservice teachers' perceptions of engineering: A learner analysis. *Education Sciences*, *9*(1), 29.

Kim, E., Oliver, J. S., & Kim, Y. A. (2019). Engineering design and the development of knowledge for teaching among preservice science teachers. *School Science and Mathematics, 119*(1), 24-34.

Mesutoglu, C., & Baran, E. (2020). Examining the development of middle school science teachers' understanding of engineering design process. *International Journal of Science and Mathematics Education, 18,* 1509-1529.

Mumba, F., & Ochs, L. (2018). A model for determining the nature and extent of integration in engineering design and science integrated activities. In *Proceedings of the Association of Science Teacher Education (ASTE) Conference,* Baltimore, MD, January 3–6, 2018.

National Research Council. (2012). A framework for K-12 science education: Practices, crosscutting concepts, and core ideas. Washington, D.C.: National Academies Press.

Nesmith, S. M., & Cooper, S. (2021). Connecting engineering design and inquiry cycles: Impact on elementary preservice teachers' engineering efficacy and perspectives toward teaching engineering. *School Science and Mathematics*, *121*(5), 251–262.

NGSS Lead States. (2013). Next generation science standards: For states, by states. Washington, DC: The National Academies Press.

Rice, M., Mumba, F., & Pottmeyer, L. (2022). Learning about Osmosis through Engineering Design Process. *The American Biology Teacher*, *84*(5), 297-307.

Schnittka, C., & Richards, L. (2016). POWERED by the Sun. *The Science Teacher*, 83(3), 25.

Thomas, D. R. (2006). A general inductive approach for analyzing qualitative evaluation data. *American Journal of Evaluation*, *27*(2), 237-246.

Windshitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific inquiry: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education*, *92*(5), 941-967.

Yaşar, Ş., Baker, D., Robinson-Kurpius, S., Krause, S., & Roberts, C. (2006). Development of a survey to assess K-12 teachers' perceptions of engineers and familiarity with teaching design, engineering, and technology. *Journal of Engineering education*, *95*(3), 205-216.

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Appendix A -Pre-Post Questionnaire

1. What is engineering?
2. Describe the engineering design process.
3. What is the difference between the scientific inquiry and the engineering design process?
4. What is a design challenge in engineering?
5. What is a design solution in engineering?
6. Explain what the following statements mean in science and engineering.
   - Asking questions (for science) and defining problems (for engineering)
   - Developing and using models
   - Planning and carrying out investigations
   - Analyzing and interpreting data
   - Using mathematics and computational thinking
   - Constructing explanations (for science) and designing solutions (for engineering)
   - Engaging in argument from evidence
   - Obtaining, evaluating, and communicating information

Appendix B: Semi-Structured Interview Protocol

1. How do you describe engineering?
2. How do you describe engineering design?
3. Walk me through an engineering design process we discussed in class *(Ask them to draw a diagram). [Most important question]*
4. Walk me through the scientific inquiry process we discussed in class. *(Ask them to draw a diagram). [Most important question]*
5. What are the similarities between Engineering Design & Scientific Inquiry?
6. What are the differences between Engineering Design & Scientific Inquiry?
7. How do you describe the following?
   a. Asking questions (for science) and defining problems (for engineering)
   b. Developing and using models in engineering design?
   c. Planning and carrying out investigations?
   d. Analyzing and interpreting data?
   e. Using mathematics and computational thinking in engineering design?
   f. Designing engineering solutions?
   g. Engaging in an argument from evidence?
   h. Obtaining, evaluating, and communicating information in engineering design?
8. Any other information on engineering design you want to share with me?

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