Interdisciplinary Engineering Education Research Collaborations: Exploring Ways of Thinking using a Mixed Methods Approach

by

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ABSTRACT

There has been a growing emphasis on the education of future generations of engineers who will have to tackle complex, global issues that are sociotechnical in nature. The National Science Foundation invests millions of dollars in interdisciplinary engineering education research (EER) to create an innovative and inclusive culture aimed at radical change in the engineering education system. This exploratory research sought to better understand ways of thinking to address complex educational challenges, specifically, in the context of engineering-social sciences collaborations. The mixed methods inquiry drew on the ways of thinking perspectives from sustainability education to adapt futures, values, systems, and strategic thinking to the context of EER. Using the adapted framework, nine engineer-social scientist dyads were interviewed to empirically understand conceptualizations and applications of futures, values, systems, and strategic thinking. The qualitative results informed an original survey instrument, which was distributed to a sample of 310 researchers nationwide. Valid responses (n = 111) were analyzed to uncover the number and nature of factors underlying the scales of futures, values, systems, and strategic thinking. Findings illustrate the correlated, multidimensional nature of ways of thinking. Results from the qualitative and quantitative phases were also analyzed together to make recommendations for policy, teaching, research, and future collaborations. The current research suggested that ways of thinking, while perceived as a concept in theory, can and should be used in practice. Futures, values, systems, and strategic thinking, when used in conjunction could be an important tool for researchers to frame decisions regarding engineering education problem/solution constellations.

DEDICATION

To my late father, Shri. Aniruddha Brahmbhatt, who has been my inspiration for all educational endeavors.

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There are many individuals to whom I owe a debt of gratitude for their support and encouragement during this journey. To my husband, Dhaval, my daily source of strength, especially when the going was slow - you knew that I could accomplish this. To my family, for unwavering support. To my dissertation committee, Dr. Leanna Archambault, Dr. Adam Carberry, and Dr. Willi Savenye, thank you for your guidance. To all the participants of this study, thank you!

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CHAPTER 1

INTRODUCTION

In light of the complex, value laden problems of a sociotechnical nature facing the world today, interdisciplinary collaborations between engineering and social sciences researchers are becoming increasingly common. The underlying goal is to implement novel ways of thinking in research for the improvement of education in engineering colleges. However, very little is known about collaborating researchers' ways of thinking and how these may influence their decisions and practices.

This introductory chapter presents the purpose of the current research project which was to provide an exploration in the ways of thinking, specifically futures, values, systems, and strategic thinking, in the context of engineering education research collaborations. The mixed methods investigation involved interviews, observations, and a survey of collaborating researchers from engineering and social sciences disciplines. The study aimed to uncover conceptualizations of futures, values, systems, and strategic thinking among engineering education researchers and explore the underlying dimensions of these ways of thinking for collaborative engineering education research.

In the following sections, I provide the rationale for research and further description of the concept of 'ways of thinking' as theorized in the field of environmental and sustainability education research. Next, the purpose of the study and specific research questions are presented. I outline the organization of this manuscript, which is written using a three-article format. Finally, I discuss the significance of the research and conclude the chapter with definitions of relevant terms.

Background

The role of an engineer in society has become increasingly important with the global challenges of climate change, alternative energies, sustainable infrastructure development, and reliable healthcare (NAE, 2004; NRC, 2017). From research applications to practical innovations, engineers constantly create solutions that connect science and technology advances to life and cater to societal needs (Grinter, 1955; Froyd & Lohmann, 2014; NSB, 2007). According to the National Academy of Engineering, “Engineering impacts the health and vitality of a nation as no other profession does” (NAE, 2004, p. 37). As a result, there is increased attention and concern over the education of future generations of engineers who will have to tackle the complex, global issues of sociotechnical nature (ASEE, 2014; Jamieson & Lohmann, 2012; NAE, 2004; UNESCO, 2012). Engineering education research (EER) is seen as an effective avenue to define the necessary elements of 21st century engineering education (Fortenberry, 2014; Haghighi, 2005).

Millions of dollars are invested in EER by a variety of agencies within the United States to find ways of improving existing engineering pedagogy and prepare the future engineering workforce. For example, the National Science Foundation’s (NSF) Engineering Directorate launched a multi-year program, the Professional Formation of Engineers (PFE), to grow and create an innovative and inclusive engineering profession with the intrinsic notion of transforming the profession. The purpose of the PFE initiative was not just the advancement of technical and professional skills, but also the “development of outlooks, perspectives, ways of thinking, knowing, and doing” (NSF, 2017, p.3).

Adopting new ways of thinking could be one of the means to achieve the needed transformation (Donofrio & Whitefoot, 2015; Henderson et. al, 2018). The EER Colloquies (JEE, 2006), held more than a decade ago, urged engineering education researchers to adopt novel ways of thinking in order to develop new pedagogical models and processes to bring transformation in the engineering education system. Since then multiple claims for adopting new ways of thinking have been made in the engineering education literature (Jamison, Kolmos, & Holgaard, 2014; NSB, 2007; McKenna, Froyd, & Litzinger, 2014). Jamison et al. (2014) indicated that engineering education researchers need novel ways of thinking to advance the state of the art in engineering education in order to prepare change agents in a broader social context. The editorial team of the April, 2014 special issue of the *Journal of Engineering Education* implored researchers to think differently, beyond the local context and short-term solutions (McKenna et al., 2014).

Novel ways of thinking could lead to innovative solutions to transform the engineering education system and solve the chronic issues of student retention, inclusion, traditional lecture-based pedagogy, and fitness of the curricula for 21st century learning. Thus, as a field, EER needs inquiries focusing on ways of thinking not only to meet changing workforce demands but also to solve chronic issues in the system, to explore engineering epistemologies within social contexts, and to promote diversity and inclusion in the profession (JEE, 2006; NSF, 2017).

Statement of Research Motivation

Numerous calls by prominent organizations have been made to transform engineering education and related research by adopting new ways of thinking (NAE, 2004; NSB, 2007; ASEE, 2014). The U.S. government has invested millions of dollars in EER through the Engineering Education and Centers directorate of the NSF. EER was also established as an area of scholarly pursuit for engineering faculty (NSF, 2008). However, there is no framework to date that characterizes ways of thinking for EER in light of the new demands for student learning. The current research sought to lay the foundational work to fill the gap in literature regarding ways of thinking that guides decisions to bring about change in engineering education.

The need for re-conceptualizing how we think about engineering education necessitates research that identifies ways of thinking that consider future sociological and technological challenges and enduring impact. Before adopting new ways of thinking, it is also necessary to better understand the existing ways of thinking of researchers for solving engineering education problems, how these ways of thinking are applied to bring about change, and what is their underlying nature that could help improve engineering education for the workforce of tomorrow. Through this inquiry, I attempt to answer these questions and argue that ways of thinking, while perceived as a concept in theory, can and should be used in practice to innovate.

Ways of Thinking in Sustainability Education

EER is an emerging and naturally interdisciplinary field that has drawn on lessons learned from other fields, including education, psychology, and the learning sciences (Borrego & Newswander, 2008; Fortenberry, 2014). Considering the need for new ways of thinking in EER, there is an opportunity to garner insights from other research disciplines, specifically, Environmental and Sustainability Education Research (ESER). EER and ESER, as emerging fields, share a common initiative of solving practical problems in their disciplines through education. ESER has focused on addressing large societal and environmental problems through education, while EER has concentrated on engineering education practices and their alignment with the changing needs of society. There is room for each field to gain insights and learn methodological approaches from one another given their inherent interdisciplinary natures and common underlying purposes (Lönngren & Svanström, 2015). In particular, ESER offers a framework, Sustainability Education Framework for Teachers (SEFT). SEFT aims to build sustainability literacy through four ways of thinking, including futures, values, systems, and strategic thinking (Warren, Archambault, & Foley, 2014).

According to the framework, futures thinking involves exploring the present with anticipatory approaches to understand and prepare for future changes, problems, and solutions. Values thinking concerns the integration of justice, equity, and ethics in designing a solution. Systems thinking is about considering holistic approaches to problem-solving that understand and analyze the complexity of various elements and their interrelationships in the overall ecosystem. Strategic thinking involves the ability to collectively develop a plan, design potential interventions, and consider possible alternatives that could lead to innovation in addressing today's challenges (Warren, et al., 2014). The current research used SEFT as a guiding framework to explore ways of thinking for EER. The framework as it applies to EER is explored in depth throughout the three studies that comprise the dissertation.

Purpose of the Research Project

With an overarching goal of developing a foundational piece for a conceptual EER ways of thinking framework, my research sought to adapt the ways of thinking proposed by the SEFT to the context of EER. Traditionally, EER has relied on collaborations between engineers and social scientists (including educational researchers, education psychologists, cognitive scientists, and learning scientists) to bring innovation to engineering education (Borrego & Newswander, 2008). These collaborations are important to assess because many NSF proposals require a partnership between an engineer and a social scientist (Wankat, Felder, Smith, & Oreovicz, 2002). The underlying notion behind mandated collaborations is to bring innovation in research methodologies and change existing engineering education practices. This begs the question of what are the ways of thinking of the collaborators for solving engineering education problems, how do they implement these ways of thinking, and what difficulties do they encounter. The current research attempted to explore these questions by adapting the SEFT for EER, particularly, in the context of interdisciplinary collaborations between engineering and social sciences researchers.

The purpose of the research was to: 1) draw upon existing literature to evaluate the concepts of futures, values, systems, and strategic thinking in relation to engineering education; 2) explore both deductively and inductively what and how researchers who work on engineering education projects think and do about futures, values, systems and strategic thinking; and 3) identify underlying factors of ways of thinking that contribute to collaborative EER.

Research Questions

The overarching goal of the current research was the development of a foundational piece for a conceptual ways of thinking framework designed to address problems in the engineering education system. Specifically, this exploratory research attempted to adapt the ways of thinking proposed by the SEFT to the context of EER. To achieve this objective, I chose to conduct the research through a series of studies and write this manuscript in an alternative dissertation format (Duke & Beck, 1999). The multiple-studies design enabled me to build each study based on the findings of the previous study and allowed for a deep, initial exploration of the ways of thinking that are used in heterogeneous engineering education projects. To address the broader goal, I framed the research around three core questions:

1. What do the four ways of thinking including futures, values, systems, and strategic thinking mean for engineering education research?
2. How do researchers participating in engineering-social sciences interdisciplinary collaborations conceptualize each of the ways of thinking, including futures, values, systems and strategic thinking?
3. What are the underlying dimensions of futures, values, systems, and strategic thinking associated with interdisciplinary engineering education research?

Ways of Thinking in EER: Three Studies Investigation

Given the dearth of prior studies in engineering education on ways of thinking and the scope of the project, I selected a three-study design for this research. Each study informed the next in order to achieve a collective coherent understanding of the phenomenon of ways of thinking as they are contextualized within EER. Though the three studies are separate, together they form a cohesive body of work that supports the goal of examining ways of thinking and underlying factors that contribute to the collaborative EER projects. The three-study design not only allowed for multiple lenses in the same inquiry (Greene, 2007), but also enabled me to build the next study with improved insights and draw interpretations based on the combined strengths of the studies together.

In the following sub-sections I present the narrative for each study design and the connections between and among the studies. Each sub-section details the purpose of the study and outlines specific research questions.

Study 1

Considering the lack of a ‘ways of thinking’ framework in EER, the purpose of the first study was to explore what the SEFT ways of thinking may look like in the context of EER. The first study introduces the SEFT and draws upon existing literature to evaluate the concepts of futures, values, systems, and strategic thinking in relation to engineering education. The specific research questions addressed by the first study include:

1. What do futures, values, systems, and strategic thinking mean in the context of engineering education research undertaken by an interdisciplinary research team?
2. How are futures, values, systems, and strategic thinking implemented and applied by the research team?

With a strong theoretical foundation and an empirical inquiry in the conceptualizations and specific examples of ways of thinking used in four collaborative EER projects, the first study validated the applicability of SEFT ways of thinking perspectives to EER and set the stage for the next deeper, qualitative inquiry.

Study 2

The purpose of the second study was to extend the empirical inquiry to a greater number of interdisciplinary EER teams. The study built on the theoretical foundation and promising results of the first study and explored the specific ways of thinking among 18 engineering and social sciences researchers, particularly in the context of their collaborative projects. Using a qualitative design, the study addressed the following research questions:

1. How do researchers participating in engineering-social sciences interdisciplinary collaborations conceptualize each of the ways of thinking, including futures, values, systems and strategic thinking?
2. How are futures, values, systems, and strategic thinking implemented by collaborating engineering and social sciences researchers in their engineering education projects?
3. What are the challenges for collaborating engineering and social sciences researchers in implementing futures, values, systems, and strategic thinking?

The rich qualitative data and analysis provided insights into what and how researchers who work on engineering education projects think and do about futures, values, systems, and strategic thinking. These insights then informed the development of an instrument for the third and final study.

Study 3

The purpose of the third study was to gather a broader understanding of the ways of thinking perspectives in collaborative EER. The information gathered from the prior qualitative study was used to create an original survey instrument to examine the number and nature of factors underlying the constructs of futures, values, systems, and strategic thinking. Using a quantitative design, the study attempted to answer the following specific research question:

1. What are the underlying dimensions of futures, values, systems, and strategic thinking associated with interdisciplinary engineering education research?

Analyzing survey responses (*n* = 111) from participating engineering and social sciences researchers the study not only uncovered the multidimensional, correlated nature of various ways of thinking but also suggested avenues to further explore and develop a 'EER ways of thinking' model in future.

In the chapters that follow, I detail each of the three studies written as collaborative manuscripts for potential publication. As a result, readers may note passive voice and use of first person (we) in the writing, as well as references to terminology such as "this paper" or "this article." Since each study is a stand-alone manuscript, the abbreviations are redefined in each study, and citations are not carried forward from the previous chapter. However, considering the nature of dissertation writing, the figures are not repeated and appendices are combined across the three studies and appear at the end.

Integration of the Three Studies

In the last chapter, I present a discussion of findings across the three studies. The quantitative findings are reexamined in light of the findings from the qualitative interviews and observations of the second study along with the theoretical insights of the first study. I expand and extend the conclusions of each individual study to triangulate and identify convergent and divergent evidence on the ways of thinking inquiry for EER (Greene, 2007, Morse, 1991). Finally, I close this manuscript addressing the limitations, directions for future research, and conclusions of the research inquiry.

Significance of the Study

The outcomes of the current research have implications for EER, engineering education teaching, and policy making. Findings on ways of thinking inquiry could serve as an organizing and motivating structure to frame decisions throughout all engineering education endeavors. First, the study adds to the existing body of knowledge on futures, values, systems, and strategic thinking by exploring how these ways of thinking apply to EER. Leveraging the ways of thinking framework developed for ESER (Warren et al, 2014), the research initiates a first step toward an 'EER ways of thinking' framework. In the process, it transcends disciplinary boundaries to identify novel ways of thinking and factors that influence how collaborating researchers think, act, and engage with their EER projects which may contribute to the success or pitfalls of the projects. Findings could guide researchers to re-conceptualize and situate their proposals for a larger overall impact in the field. In addition, recommendations from this research could be especially helpful to engineering and education faculty members who are planning to collaborate.

Second, there is a direct link of any EER to engineering classrooms. New skill-sets and related thinking abilities required from future engineers to solve sociotechnical and/or interdisciplinary problems pose a pedagogical challenge for engineering faculty. The outcomes of this study could provide guidance for engineering faculty to prepare their students.

Third, identifying and understanding ways of thinking that influence interdisciplinary engineering education collaboration could guide the decision-making for policymakers and funding agencies. An understanding of how engineering education researchers think regarding the needed transformation in the system could be helpful in setting the future direction of proposal calls.

Finally, this study has the potential to provide valuable insight into real-world interdisciplinary projects that can be relevant in different settings. The challenges faced by the world today are multifaceted and are in desperate need for successful interdisciplinary collaborations that have the capacity to address complex problems. Whether in engineering, science, business, or the arts, whether in the industry or academia, cross-disciplinary collaborations have become essential for the workforce today. A ways of thinking model developed from this study for interdisciplinary EER could also offer guidance for interdisciplinary research in other fields.

Definition of Relevant Terms

Below is a list of relevant terms with definitions that are used throughout the study. The terms are organized in the order in which they are referred to in this manuscript.

- **Ways of Thinking**: Ways of thinking is a systematic thought process that informs decision-making (Warren et al., 2014). According to Harel and Sowder (2005), it is an approach to solving complex problems through coherent patterns in reasoning. I operationalize ways of thinking as an approach to solving problems. It is not a heuristic. It is the way in which engineering education researchers think, act, and engage with their interdisciplinary collaborative research.
    - **Futures thinking** is about working to address tomorrow's problems today with anticipatory approaches to understand and prepare for future changes,

problems, and solutions (Warren et al., 2014). It is a "navigational tool" for changing the nature of decision-making in the present while conceptualizing future scenarios (Miller, 2003).

  - **Values thinking** is about recognizing the concepts of ethics, equity, and social justice (Warren et al., 2014). It involves understanding these concepts in the context of varying cultures and accordingly making decisions.
  - **Systems thinking** involves considering holistic approaches to problem-solving that understand and analyze the complexity of various elements and their interrelationships in the overall ecosystem (Warren et al., 2014). It is the ability to see the interdependencies between parts and conceive problems considering cascading effects on other elements (Fordyce, 1988).
  - **Strategic thinking** is the ability to create a plan of action to achieve the desired vision (Warren et al., 2014). It involves envisioning long-term goals and objectives, collectively developing a plan, and considering appropriate courses of action and resource allocation that could lead to innovation in addressing today's challenges (Wiek, Withycombe, Redman, & Mills, 2011b).

- **Interdisciplinary Collaboration**: Interdisciplinary collaboration indicates research practices that integrate separate disciplinary concepts, theories, methods, and tools to create a coherent understanding of the problem which would not have been possible through a single disciplinary lens (Adams, Mann, Jordan, & Daly, 2009; Miller & Mansilla, 2004; Ornelas, 2015). The term interdisciplinary suggests an interactive nature that is applied to the collaboration. There is a cognizant effort to integrate numerous disciplinary insights through deliberate coordination and greater interaction, though the members of interdisciplinary collaborations continue to retain their discipline-specific perspectives. In interdisciplinary collaborations, the meaning-making takes utmost importance as researchers share their domain-specific expertise, interpret multiple perspectives and decide on strategies to address issues at hand (McKenna, Yalvac, & Light, 2009).

CHAPTER 2

WAYS OF THINKING: IN THEORY AND RESEARCH PRACTICE

This chapter details the first phase of the research, designed to explore ways of thinking among researchers collaborating for interdisciplinary EER. The chapter builds on the rationale presented in the previous chapter through an extensive theoretical review and an initial qualitative inquiry. The ways of thinking as a lens to consider and address complex engineering education challenges is grounded by: 1) outlining the conceptual framework briefly introduced in the previous chapter; 2) defining futures, values, systems, and strategic thinking, borrowing from literature in environmental and sustainability education research (ESER), learning sciences, educational psychology, and business; and 3) synthesizing a breadth of literature in EER to demonstrate the relevance of the ways of thinking perspectives to engineering education.

The second half of this chapter describes an empirical inquiry conducted to validate the applicability of ways of thinking perspectives to EER. The empirical investigation included interviews of eight engineering and social sciences researchers. Findings of the qualitative inquiry revealed the conceptualizations and specific examples of ways of thinking used in collaborative EER. Results indicated that ways of thinking when integrated, offered a networked approach for collaborators to frame decisions regarding engineering education research.

Overall, this study contributes to the literature base by introducing the SEFT to EER. The current chapter presents the first of the three studies, written as a manuscript for publication, which sets the stage for the second qualitative inquiry. Readers may notice that citations and abbreviations from the previous chapter are not carried forward.

Introduction

There is increased attention and concern over the education of future generations of engineers who will have to tackle the complex, global issues of sociotechnical nature (ASEE, 2014; Jamieson & Lohmann, 2012; NAE, 2004; UNESCO, 2012). Engineering education research (EER) is an effective avenue to define the necessary elements of 21st century engineering education (Fortenberry, 2014; Haghighi, 2005). The National Science Foundation (NSF) invests millions of dollars in EER to create an innovative, interdisciplinary culture aimed at radical change in the engineering education system, as evident from this quotation from the *Engineering Societies and Undergraduate Engineering Education: Proceedings of a Workshop*:

> 'You don't start from I want to do this activity,' said Douglas. 'You start from I want to make this cultural change. That's a very different way of thinking. Let's think about how to not just cross-fertilize but cross-collaborate and create these larger partnerships that can work more broadly and at a larger scale to impact the engineering education field. What we want is broad, radical change in engineering education.' (p. 8)

Adopting new ways of thinking is seen as one necessary means to achieve the needed transformation of the system (JEE, 2006; NSB, 2007; Henderson et. al, 2018). For example, the 2015 report from the National Academy of Engineering states, "The more perspectives and life experiences and ways of thinking a team brings to a problem, the more ideas are likely to be generated" (Donofrio & Whitefoot, 2015, p.79). The EER Colloquies (JEE, 2006) held more than a decade ago also urged researchers to adopt novel ways of thinking and develop new pedagogical models and processes that could bring transformation in the engineering education system. Multiple claims for adopting new ways of thinking have been made since then in the engineering education literature (Case & Light, 2011; Jamison, Kolmos, & Holgaard, 2014; Kabo & Baillie, 2009; NSB, 2007; McKenna, Froyd, & Litzinger, 2014). Kabo and Baillie (2009) emphasized new ways of thinking in engineering programs that create awareness of environmental, cultural, economic, and social impacts of engineering on society. Case and Light (2011) argued for new ways of thinking about the research process in order to expand methodological range and address different questions. McKenna et al. (2014) implored researchers to think differently, beyond the local context and short-term solutions, to transform the engineering education system (McKenna et al., 2014).

This body of literature taken together suggests that EER as a field needs new ways of thinking, not only to meet changing workforce demands, but also to solve chronic issues plaguing the system, as a means to increase awareness of the social impacts of engineered solutions, explore engineering epistemologies within social contexts, and promote diversity and inclusion in the profession (Case & Light, 2011; Jamison et al., 2014; McKenna et al., 2014; NSB, 2007; Cabo & Baillie, 2009). There is an emerging consensus that the adoption of new ways of thinking has not been fully addressed since the 2006 call from the colloquies. The urgency to adopt new ways of thinking was most recently recognized when The Engineering Directorate of the NSF launched a multi-year program, the Professional Formation of Engineers (PFE), to develop “outlooks, perspectives, ways of thinking, knowing, and doing” to create an innovative and inclusive engineering profession (NSF, 2017, p.3).

The expression ‘ways of thinking’ has been used frequently in the referred literature to describe a particular way of engaging with a problem. We attempt to draw a distinction between general ways of thinking and what we have identified as productive ways of thinking specifically for engineering education. We argue that ways of thinking, while perceived as a concept in theory, can and should be used in practice to innovate. This paper takes an exploratory yet critical look at ways of thinking for engineering education and research. The goal of this work is threefold: 1) provide an appreciation for ways of thinking perspectives with a theoretical foundation, 2) present experimental validity on ways of thinking perspectives, and 3) initiate a vision for an EER ways of thinking framework. A work in progress paper regarding the initial efforts of this study was presented at the 2018 Annual Conference for the American Society for Engineering Education (Dalal & Carberry, 2018).

In the following sections, we operationalize ways of thinking and present a framework that conceptualizes four specific ways of thinking for addressing complex, educational challenges. The first half of the paper reviews existing literature and contextualizes the framework for engineering education and research. The second half of the paper builds on the theoretical underpinnings using a qualitative investigation and illustrates how the ways of thinking could apply to engineering education and related research. We explore conceptualizations and authentic examples of ways of thinking among engineering and social sciences faculty who collaborated to conduct interdisciplinary research. The final component of the paper is a critical reflection of the experimental insights, avenues for further exploration, and broader implications for various stakeholders within the engineering education ecosystem.

Ways of Thinking

The current study is grounded in the understanding of ways of thinking, which represents a lens for considering and addressing complex challenges. David Sousa (2016), in his book, *How the Brain Learns,* defined thinking as:

> easier to describe than to define. Its characteristics include the daily routine of reasoning – where one is at the moment, where one's destination is, and how to get there. It includes developing concepts, using words, solving problems, abstracting, intuiting, and anticipating the future (p. 246).

Sousa further noted that creativity, communication, logic, generalization, anticipation, intuiting, valuing, and conceiving are some of the different ways of thinking that ultimately manifest in our actions and behaviors. Educational researchers have frequently attempted to describe various ways of thinking including cultural, logical, pragmatic, mathematical, and language-oriented thinking (Harel, 2008; Merryman, 1986; Meyer & Land, 2003; Slobin, 1996). Harel and Sowder (2005) defined ways of thinking as an approach to solving complex problems through coherent patterns in reasoning. This definition has been further expounded upon in the field of ESER as a lens for considering and addressing complex challenges (Warren, Archambault, & Foley, 2014).

We operationalize ways of thinking using these definitions as a systematic thought process that informs decision-making. Ways of thinking is not a heuristic, but an approach with which researchers think, act, and engage in their engineering education projects.

Guiding Framework

As an emerging and naturally interdisciplinary field, EER has drawn on lessons learned from other fields, including education, psychology, and the learning sciences (Borrego & Newswander, 2008; Fortenberry, 2014). ESER is a similarly emerging and interdisciplinary field offering yet another field from which EER can garner insights, particularly because both fields share a common underlying purpose of solving complex, practical problems through education (Lönngren & Svanström, 2015). Within the field of ESER, the SEFT, is a conceptual framework for considering complex problems and solutions through four specific ways of thinking: 1) futures, 2) values, 3) systems, and 4) strategic thinking (Warren et al., 2014).

Warren et al. (2014) recognized the need for a conceptual, logical framework to build sustainability literacy in order to address complex sustainability challenges through education. They proposed futures, values, systems, and strategic thinking as four essential ways of thinking to link different sustainability topics and build capacity for educators to understand the complexity of sustainability issues (Figure 2.1). *Futures thinking* focuses on exploring the present with anticipatory approaches to understand and prepare for future changes, problems, and solutions. *Values thinking* concerns the integration of justice, equity, and ethics in designing a solution. *Systems thinking* considers holistic approaches to problem-solving as ways to understand and analyze the complexity of various elements and their interrelationships in the overall ecosystem. *Strategic thinking* involves the ability to collectively develop a plan, design potential interventions, and consider possible alternatives that could lead to innovation in addressing today's challenges (Warren et al., 2014).

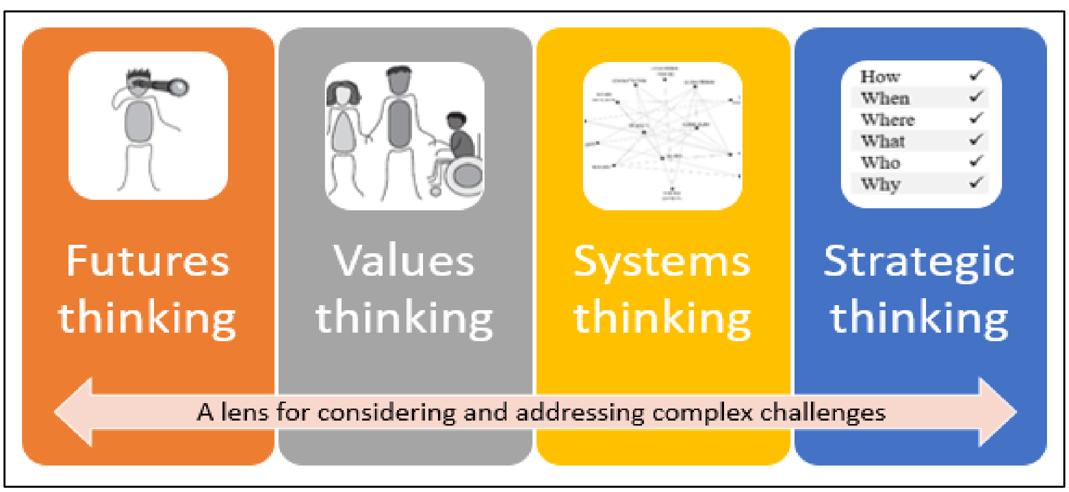

Figure 2.1. Different ways of thinking conceptualized under the SEFT.

The four ways of thinking combined present a networked approach for questioning, researching, and reflecting in complex, interdisciplinary, and interpersonal situations. We argue that these four ways of thinking, while originally conceived for sustainability education, apply to EER when adapted for problem-solving and addressing complex challenges. The following sections explain each way of thinking through grounded support in the EER and ESER literature, as well as from broader fields including education, psychology, and business. We then describe what they could mean to the context of engineering education and discuss why these specific ways of thinking are important to examine for engineering education and related research.

Futures Thinking

What is futures thinking? Futures thinking, also known as anticipatory thinking, focuses on working to address tomorrow's problems today (Warren et al., 2014). It entails learning from past decisions, understanding the present scenario, and anticipating possible consequences of today's actions (or non-actions) for future generations (Wiek, Withycombe, & Redman, 2011a). It should be noted that futures thinking is not about forecasting or predicting, but rather about conceptualizing hypothetical futures often at least 20 years ahead of current time (OECD, 2017). Miller (2003) refers to futures thinking as a "navigational tool" for changing the nature of decision-making in the present. Alper (2016) conceptualized futures thinking as an effort to "think broadly, think big picture, and think way out of the box" when considering the changes that may occur in the field of engineering education in the next few decades (p. 4).

Futures thinking includes the ability to:

- "Collectively analyze, evaluate, and craft rich 'pictures' of the future" (Wiek et al., 2011a, p. 208-209)
- Project an idea or design into the future and anticipate its positive and negative consequences (Radcliffe, 2005)
- Identify emerging issues, possible outcomes, potential threats, and exciting opportunities (NAS, 2007)
- Think about examples and approaches to convey how research can help humanity and life (NSB, 2007)
- Connect a "collection of methods, theories, and findings" in a constructive manner looking at the future (Miller, 2003, p. 7)
- Recognize the rapid pace of change in the world as well as uncertainty and ambiguity in the contextual environment (Burt & van der Heijden, 2003)
- Believe in more than one future and pro-actively engage in scenario-building to envision alternative futures (Inayatullah, 2008)

Futures thinking in engineering education and research. The system of engineering education has traditionally focused on imparting technical skills aligned with the present day demands of industry and needs of society (Mann, 1918, Wickenden, 1930, Grinter, 1955); however, there are a few conclusive examples of futures thinking in the evolution of the field. An analysis of the trends by the Goals Committee (1968) resulted in a call for the need to define the direction of the field looking ahead to year 2000. The much more recent *The Engineer of 2020* report (NAE, 2004) alludes to the fact that approaches of the past, while successful in examining current needs of that time, were not enough to meet future needs that entailed changing demographics and complex interrelationships of disciplines. The report emphasized futures thinking as a way of expanding the appreciation of possible futures, visualizing probable futures, and creating bold new paradigms for preferred futures (NAE, 2004). The National Academy of Sciences observed a similar "recurring pattern of abundant short-term thinking" (NAS, 2007, p. 25) and urged researchers, policymakers, and funding agencies to engage in long-term aspirational thinking. These reports place heavy emphasis on the need to utilize futures thinking.

Futures thinking concerns advancing the state of the art in engineering education, not only to keep pace with technological advances, but also to address complex societal problems. Prior research has identified that the long-term sustainability of society is closely associated with the potential impact of design and design engineering through futures thinking (Gattie, Kellam, Schramski, & Walther, 2011; Lande & Leifer, 2010). This means that researchers need to develop interventions for students to practice engineering design while imagining plausible, sustainable futures. The emerging body of research recognizing today's students as change agents for a positive tomorrow hints at futures thinking being a driver to better prepare the next generation. (Jamison & Mejlgaard, 2010; Jamison et al., 2014; Johri & Olds, 2011; Sunthonkanokpong, 2011). A futuristic world with broad social context and cultural concerns requires transformation in the learning and instruction provided to the future workforce.

Futures thinking also entails understanding and accepting uncertainty (Warren et al., 2014). Though traditionally engineers are trained to eliminate uncertainty (Lande & Leifer, 2010), futures thinking suggests that the engineering education system needs to prepare the future workforce to handle ambiguity and make choices based on anticipatory changes (Borrego & Henderson, 2014; Huntzinger, Hutchins, Gierke, & Sutherland, 2007).

Futures thinking is concerned with developing models, processes, and practices, to adaptively prepare for future changes, problems, and solutions that actually influence the larger engineering community (Alper, 2016; McKenna et al., 2014). It involves considering dissemination and adoption of research beyond academic readership (Finelli, Daly, & Richardson, 2014; Jesiek, Newswander, & Borrego, 2009), imagining disruption of existing patterns to bring on needed transformation (Borrego & Henderson, 2014), and rescoping problem spaces to allow for innovative solutions to future problems (Lande & Leifer, 2010).

The cumulative research presented suggests the need to reposition engineering education with a futures-based approach to include thinking about what could happen, as opposed to what will happen. Researchers should envision where engineering education needs to go and how to get there. Consequently, futures thinking involves connecting diverse aspects of present-day research findings to envision plausible future scenarios through informed reflection (Wiek et al., 2011a). It entails “what engineering students should learn in the university to prepare for the future and how this might differ from what is taught today” (NAE, 2004, p. xiii).

Values Thinking

What is values thinking? Values thinking is also known as ethical thinking, normative thinking, or value-focused thinking (Warren et al., 2014). Vesilind (1991) clarifies that values thinking is not as much about ethical theories or moral values, as it is about recognizing the concepts of ethics, equity, and social justice. It involves understanding these concepts in the context of varying cultures and accordingly making decisions (Vesilind, 1991; Warren et al., 2014). Values thinking is also concerned with reflexivity in research. It is the reflexivity to draw connections between external value systems and research practice (Guston, 2013). Stilgoe, Owen, and Macnaghten (2013) further clarify values thinking and reflexivity as “holding a mirror up to one’s own activities, commitments and assumptions, being aware of the limits of knowledge and being mindful that a particular framing of an issue may not be universally held” (p. 4). Values thinking includes the ability to:

- Assess a problem and its context comprehensively within and across cultures (Warren et al., 2014a)
- Discuss how decisions can be made, not which decisions are the correct ones (Vesilind, 1991)
- Include all segments of users when designing solutions (Wiek, Withycombe, Redman, & Mills, 2011b)
- Collaborate with stakeholders for critical consideration of a given situation, including both positive and negative aspects from a variety of perspectives (Veugelers, 2000)
- Understand liabilities with fair distribution of risks and benefits (Guston, 2013)
- Recognize cultural norms, including conscious and unconscious statements of values (Vesilind, 1991)
- Recognize micro-inequities in the system in order to understand the “non-inclusive” groups’ experience (McKenna, Dalal, Anderson, & Ta, 2018)

- Engage with social worlds and draw connections between external value systems and scientific practice (Stilgoe et al., 2013)
- Identify and consider the consequences, risks, and disadvantages of engineered solutions (Sarkikoski, 1988)

Values thinking in engineering education and research. The multi-faceted system of engineering education interprets values thinking in various ways in the literature considering diversity and inclusion, social-humanistic approaches of research, and ethical engineering practices.

The EER Colloquies recognized the need for diverse viewpoints and fair engineered solutions (JEE, 2006). They called for an engineering education system that reflects the society and provides social and ethical knowledge in addition to technical knowhow. Several well-known issues persist in the system regarding a significant gender gap, underrepresented minorities, and an overall chilly climate toward non-dominant groups (McKenna et al., 2018; Riley, Slaton, & Pawley, 2014). Values thinking for many researchers has become focused on mirroring the society in the engineering education system considering diversity (Lichtenstein, Chen, Smith, & Maldonado, 2014; Mills, Ayre, & Gill, 2011; Swan, Paterson, & Bielefeldt, 2014). It is about challenging the status quo and creating a culture of inclusion. The finer grained consequence of viewing values thinking in such a way is that it translates into designing community engagement opportunities, developing inclusive pedagogies, championing wide diversity and inclusion efforts, and designing outreach activities that take access for underserved populations into account (Abaid, Kopman, & Porfiri, 2013; Lumsdaine & Lumsdaine, 1995; McKenna et al., 2018; Swan et al., 2014).

Values thinking also entails recognition of the social-humanistic side of the engineering education system. This means appreciating diverse ways of knowing and considering contextual and individual experiences in research methodologies (Douglas, Koro-Ljungberg, & Borrego, 2010; Riley et al., 2014; Sarkikoski, 1988). For example, Sarkikoski (1988) wrote, “Social development has become the problem of technological thinking and engineering education,” which necessitates ethical thinking, other ways of knowing, and system reform (p. 342). Riley et al. (2014) argued for a move beyond “positivist ways of knowing” toward “inclusive and reflexive inquiry” that would consider context and experiences (p. 339). Values thinking thus entails consideration of distinct voices and representation among participants keeping in mind diversity of class, nationality, queerness, disability, or age.

Finally, values thinking is also about ethically-grounded engineers who see themselves as global citizens and “understand how to adapt solutions in an ethical way” (NAE, 2004, p. 21). A number of studies discuss values thinking considering responsible engineering practice and ethical standards that go beyond the controlled lab environment (Barry & Herkert, 2014; Guston, 2013; NAE, 2004; Stilgoe et al., 2013). The world today faces complex problems of a sociotechnical nature that are value laden. Sarkikoski (1988) concluded that technical and social problems, though seemingly different in nature, demand a coherent solution, which directly relates to values thinking. Researchers and educators need to embrace values thinking to bring about deliberate change within existing cultures and practices (Swan et al., 2014). They need to teach future engineers about making choices for specific values that are fair, transparent, and equitable (Veugelers, 2000), while considering unintended consequences of a designed solution

(Wiek et al., 2011b). Values thinking in engineering education then translates into creating associations between moral values and technical subjects (McCuen, 1992; Vesilind, 1991). Examples could include integrating the topic of public health when teaching technical details of waste management systems or talking about historical preservation when lecturing about land development (McCuen, 1992).

The whole of the literature suggests that values thinking is a crucial component of any empirical inquiry to bring deliberative change in the existing culture. It involves an understanding of culture, a willingness to interact with all stakeholders, and a desire to help humanity and life (NSB, 2007). Engineering products and solutions will hold little significance without values thinking (Barry & Herkert, 2014).

Systems Thinking

What is systems thinking? A system is a bounded entity of many elements or sub-systems that function as a whole through the intricate web of interrelationships (Fordoyce, 1988). Systems thinking is a holistic approach to problem solving that keeps in mind the interdependencies of its sub-systems and elements (Warren et al., 2014). It involves the ability to see interdependencies between parts while also working with the whole (Godfrey, Crick, & Huang, 2014). Warren et al. (2014) note that systems thinking does not equate to complete knowledge, but rather to an understanding of structures, functions, and causal loops. It is about understanding the notions of delay, uncertainty, and nonlinearity that add to the complexities of dynamic behavior of a system (Spector & Davidsen, 1997).

Wiek et al. (2011a) point out that the ability to analyze system dynamics also involves an understanding beyond causal loops and feedback, to include acumen of perceptions, intent, decisions, and constraints. This suggests that systems thinking also entails an awareness that every problem is situated in a bigger context, realization of the consequences of an action, ability to understand constraints and make connections, and acceptance that there might be elements invisible at any given moment, but that these elements govern the system nonetheless (Meadows, 2008; Senge & Sterman, 1992). Systems thinking includes the abilities to:

- Consider cascading effects, feedback loops, and system states (Warren et al., 2014)
- "Analyze system dynamics to make informed decisions that reduce the risk of negative outcomes" (Warren et al., 2014, p. 8).
- Assess system complexity "across different domains (society, environment, and economy) and across different scales (local to global)" (Wiek et al., 2011a, p. 207)
- See true causes of the problem that are further in time and space and may originate from different parts of the system (Nehdi & Rehan, 2007)
- Uncover different knowledge systems through which an engineering problem in a particular territory can be perceived and then explore different parameters and measurements that could be applied (Godfrey et al., 2014)
- Conceptualize a situation in a bigger context and articulate problems in new and different ways (Stroh, 1994)
- Recognize that there are no perfect solutions and that the choices made will have an impact on other parts of the system (Meadows, 2008)

Systems thinking in engineering education and research. The larger system of engineering education primarily focuses on the institution, administrators, students, faculty and curricula; but also includes the sub-systems of accreditation boards, industry, federal agencies, professional bodies, primary and secondary education, the global economy, and public perceptions (McKenna et al., 2014; NAE, 2008). Fordyce (1988) clarified that while engineering is primarily “about the design, management, and maintenance of systems,” systems thinking in relation to engineering education refers to “the way in which engineering problems are conceived” considering the cascading effects on all the elements of the larger ecosystem (p. 285).

The system of engineering education from its inception has been grappling with multiple chronic issues of student retention, diversity, inclusion, overloaded curricula, and traditional lecture-based pedagogy (Goals Committee, 1968; NAE, 2004). Past research has illuminated the need for systems thinking to address these issues and transform the system (Borrego & Henderson, 2014; McKenna et al., 2014). Systems thinking broadens the problem space and facilitates the asking of new questions, thereby expanding the choices for a solution. Due to its non-linear nature, systems thinking illustrates how incremental changes can bring about transformation in the system because of cascading effects (Warren et al., 2014).

EER needs to better understand the ecological systematic transformation process that conveys the totality of all causal relationships. Of particular interest is the positive and negative feedback loops from the peripheral elements (e.g., K-14 school systems, university policies, international partnerships, accreditation bodies, and funding agencies) that influence a significant change in the core of the system that comprises of the administrators, students, faculty, and curricula. Spector and Davidsen (1997) wrote, “It is often people’s perceptions and goals that give rise to dynamic behavior” (p. 129). Researchers could apply systems thinking to integrate people, purposes, processes, and performance to better grasp the impact of feedback loops.

Systems thinking also ties in with the preparation of the future workforce. A recent National Research Council report suggested that the next generation of engineers will be challenged to find solutions to problems situated within social and economic systems such as water, energy, transportation, healthcare, environment, and housing (NRC, 2012). These complex, societal problems will demand understanding of perceptions, intent, decisions, and constraints as part of systems thinking (Wiek et al., 2011a). Accordingly, engineering education researchers need to design experiential learning activities that encourage thinking with respect to loops, layers, and processes. Researchers need to create models that help understand the properties and relationships of a range of systems and sub-systems in order to prepare the future workforce for the inevitable complex sociotechnical challenges that will arise (Godfrey et al., 2014). Only by understanding the whole system structure, will we be able to progress toward more satisfying, long-term solutions to the chronic problems plaguing the system (McKenna et al, 2014).

Strategic Thinking

What is strategic thinking? A strategy is a plan of action, which makes strategic thinking the ability to create a plan of action to avoid undesirable scenarios and achieve a desired vision (Warren et al., 2014). Strategic thinking involves envisioning long-term goals and objectives and considering appropriate courses of action and resource allocation to be able to meet specified goals (Lawrence, 1999). In other words, strategic thinking is the ability to "get things done" (Wiek et al., 2011a, p. 210). Strategic thinking, strategic planning, futures thinking, and critical thinking are terms that are often used interchangeably, but do in fact hold different meanings. Lawrence (1999) clarified the difference between strategic thinking and strategic planning when he explained that strategic thinking is a creative, divergent process that involves synthesis, while strategic planning is a conventional, convergent process that is analytical and is used "to operationalize the strategies developed through strategic thinking and to support the strategic thinking process" (Lawrence, 1999, p. 10). Bassett (2012) further clarified the difference between these two terms suggesting that strategic thinking should occur on a regular basis as part of daily activities, while strategic planning happens only periodically.

The clarification between strategic thinking and futures thinking is needed because strategic thinking is future-oriented. The difference is that futures thinking tends to imagine a preferred, most likely future and works "backward to map out the sequence of decisions and actions necessary to reach the assumed future" (Darji & Jani, 2009, p. 47). Strategic thinking is the more rigorous process of evaluating novel strategies to respond promptly and effectively to unforeseen circumstances. Strategic thinking and critical thinking are often confused terms because strategic thinking uses critical thinking as a tool (Lawrence, 1999). Critical thinking involves the evaluation of the content on hand, whereas strategic thinking goes beyond and analyzes consequences, implications, and indirect effects due to interdependencies in the larger context, considering both the short-term and longer-term objectives. Strategic thinking is where the abilities that comprise systems and futures thinking are translated into action for change (Wiek et al., 2011b).

Strategic thinking includes the ability to:

- Frame every decision by how it contributes to achieving a particular vision (Warren et al., 2014)
- Allocate resources of time, talent, and budget more effectively (Darji & Jani, 2009)
- Explore below the surface of the issues to uncover insights (Warren et al., 2014)
- Identify a few thrust areas for future development (Halpin & Huang, 1995)
- Work with the system and leverage resources (Stollar, Poth, Curtis, & Cohen, 2006)
- Discern real-world situations and relationships, logistics, and changing political positions (Wiek et al., 2011a)
- Negotiate with all stakeholders to collaboratively achieve the vision (Wiek et al., 2011a)
- Shape and re-shape the intent continuously (Lawrence, 1999)
- Adopt ‘intelligent opportunism’ to take advantage of the situation (Jasinski, 2004; Lawrence, 1999)
- Shift direction and/or discontinue projects based on trend data (Halpin & Huang, 1995)

Strategic thinking in engineering education and research. A wealth of literature has examined critical thinking in the context of engineering education (Ahern, O'Connor, McRuairc, McNamara, & O'Donnell, 2012; Woods, Felder, Rugarcia, & Stice, 2000), but little has been done around the study of strategic thinking in the field because it is often perceived as a leadership skill (Bolman & Deal, 1991). However, creative problem solving strategies conceived as part of strategic thinking could help address complex engineering education problems (Lumsdaine & Lumsdaine, 1994). The National Research Council indicated the need for strategic thinking in EER to stay aware of the potential disruptive advances in the field by looking at the big picture (NRC, 2012). Others have recommended strategic thinking to create diverse solutions for global impact, communicate with stakeholders, and consider novel ways of applying research beyond academic writing (Jesiek, Borrego, & Beddoes, 2010; NAE, 2008). Strategic thinking for researchers could also translate as recognition of systemic inertia, barriers, and alliances and understanding of "viability, feasibility, efficiency, and efficacy" of interventions (Wiek et al., 2011b).

The converging forces of globalization, technology, and economic restructuring also make strategic thinking an essential skill for the future workforce (Liao, Chen, & Wu, 2006). An example from the multinational oil and gas company, Shell, indicated that engineers will need emotional and social intelligence, synthesizing capabilities, and strategic thinking, in addition to technical knowledge, as managers of such companies and project teams (De Graaff & Ravesteijn, 2001). The present generation of students will have to shift from a do-er mode to a thinker mode. The demands for these thinking skills then have consequences for engineering education. Researchers need to design interventions incorporating real-world projects or interactive simulations to develop strategic thinking on the part of students (Davidovitch, Parush, & Shtub, 2006; Garcia-Perez & Ayres; 2012; Redd, Dellacamera, & Levesque, 1997). Researchers should also consider the adaptation of existing curricula to focus on processes rather than products. As *The Engineer of 2020* report explained, “using new strategic planning tools, we should reconstitute engineering curricula and related educational programs to prepare today’s engineers for the careers of the future” (NAE, 2004, p. 51).

Ways of Thinking as an Integrated Approach

We see futures, values, systems, and strategic ways of thinking as four main compartments of a researcher’s toolkit used to critically engage with the surrounding world. These ways of thinking provide an organizational structure if considered individually, but they should also be connected in practice because they mutually augment one another. For example, strategic thinking can use a systems approach to achieve a desired goal. Futures thinking might consider projected numbers of societal demographics and bring in values thinking while envisioning long-term scenarios. Alternatively, these ways of thinking may also create conflict under certain situations. Acting upon values thinking may not align strategically with the direction of the project. This is the very reason why a networked approach of integrating the ways of thinking becomes crucial. What we ultimately need in order to be able to solve complex educational issues, is the integration of all four ways of thinking “rather than relying on piecemeal processes that highlight particular dimensions and not others” (Stilgoe, 2013, p. 7).

The combined four ways of thinking build capacity for researchers and practitioners alike to be able to understand the broad and complex nature of engineering education challenges, conceptualize problem-oriented solution driven studies, and recognize the connections between research and practice. As a conceptual framework, futures, values, systems, and strategic ways of thinking offer organizing principles for questioning, researching, and reflecting in interpersonal, interdisciplinary situations. Implementation is not meant to be prescriptive as each way of thinking can be implemented with one another, in parallel, or in an isolated fashion, depending on the situation (Warren et al., 2014). We see them as four lenses that provide an opportunity to extend and enhance any engineering education inquiry.

The next sections of this paper illustrate further understanding of the proposed 'ways of thinking' within four interdisciplinary engineering education projects. Guided by the SEFT framework, we conducted an empirical inquiry to better understand how futures, values, systems, and strategic ways of thinking are conceptualized and implemented by collaborating engineering and social sciences researchers. The following sections explain the rationale for selecting interdisciplinary collaborations, describe the methods used, and discuss key findings from the application of the framework.

Ways of Thinking in Action: An Illustrative Study

Interdisciplinary EER and Ways of Thinking

A well-established body of research has shown the significance of interdisciplinary collaboration between engineers and social scientists (Carr et al., 2017; McKenna, Yalvac, & Light., 2009; Olds, Moskal, & Miller, 2005). The collaborative research typically involves drawing on theories and research methods from learning sciences, instructional design, and educational psychology, and then applying them to the teaching and learning processes in the engineering domain. Some examples include creating more inclusive engineering course designs, using new pedagogical approaches in engineering classrooms, understanding mental models of students, or integrating engineering into traditional science and mathematics education at the K-12 level (Aurigemma, Chandrasekharan, Nersessian, & Newstetter, 2013; Carberry & Church, 2009; Dalal et al., 2017; Ganesh & Schnittka, 2014).

The underlying notion behind the collaborations is to change existing pedagogical practices and culture across the system of engineering education through innovative interdisciplinary research. NSF invests in interdisciplinary EER and often mandates an engineer-social scientist partnership (NSF, 2008; Wankat et al., 2002). One example is the Research Initiation in Engineering Formation award under the Professional Formation of Engineers program (NSF, 2017). The program specifically intends to develop "outlooks, perspectives, and ways of thinking, knowing, and doing" in order to "create an innovative and inclusive engineering profession" (NSF, 2017, p. 3). Utilizing the ways of thinking framework proposed earlier, we examined the futures, values, systems, and strategic thinking of interdisciplinary engineer-social scientist research teams, specifically the primary investigator and co-primary investigator pairs. The research questions guiding this proof of concept study include:

1. What do futures, values, systems, and strategic thinking mean in the context of engineering education research undertaken by an interdisciplinary research team?
2. How are futures, values, systems, and strategic thinking implemented and applied by the research team?

Method

Participants

Four engineer-educator dyads were purposefully selected using maximum variation sampling (Creswell, 2014) to find shared patterns among ways of thinking that cut across heterogonous engineering education projects at a doctoral university with very high research activity in the United States (The Carnegie Classification, n.d.). Maximum variation sampling considered the context of the collaboration which included undergraduate engineering education (UG), K-12 settings (K-12), and education programs within engineering research centers (ERC). Table 2.1 provides a summary of participant details, organized in descending order by years of collaboration. All 8 participants were assigned a pseudonym to ensure confidentiality.

Table 2.1

Participant Details

	Dyad A		Dyad B		Dyad C		Dyad D	
Participants	Kyle	Betty	Kelly	Wendy	Nick	Laura	Henry	Janelle
Program*	MSE	ED	CSE	LS	GE	ED	EE	LS
Project Context	Undergraduate teaching (UG)		High school science textbook (K-12)		Specialty courseware (ERC)		Summer research experience (ERC)	
Years of Collaboration	13		4		3		1.5	
Publications Journal/ Conference	6/44		1/5		0/2		0	

* MSE: Materials Science Engineering; ED: Education; CSE: Computer Science & Engineering; LS: Learning Sciences; GE: Geotechnical Engineering; and EE: Electrical Engineering

Data Collection

Data sources included 60 to 90-minute, semi-structured, dyadic interviews with collaborating engineering and social sciences faculty. The interviews were designed to elicit understandings about futures, values, systems, and strategic thinking from the collaborating researchers. Dyadic interviews were used to bring interaction into the interview. This intentional step expands coverage of the research topic because participants must differentiate their thoughts and talk about ideas that might not have occurred to them individually, particularly when participants share a preexisting relationship (Morgan, Eliot, Lowe, & Gorman, 2016; Morris, 2001). Institutional Review Board approval was obtained (Appendix A). Dyads were first asked to describe their collaborative projects followed by a few minutes of individual reflection that included writing about thinking tied to various project decisions. The reflection activity was designed and incorporated because analysis of one's own thinking and actions requires metacognitive skills which are not easy to elicit (Pope, 2012). Reflecting through writing helps participants verbalize their thoughts (Gass & Mackey, 2000). Next, the participants were shown a four-quadrant grid of ways of thinking as defined by SEFT (Figure 2.2). The dyads were then prompted to discuss how they conceptualized the four ways of thinking for engineering education and research. Teams were also asked if these ways of thinking played a part in their collaborative projects and if so, how.

Futures thinking Anticipatory approaches to understand how today's solutions could impact the future of the field - future changes, problems, and solutions.	Values (Ethical) thinking Understanding concepts of justice, equity, and ethics across and within cultures, and integrating them while designing a solution.
Systems thinking Considering holistic approaches to problem-solving that understand and analyze the complexity of various elements and their interrelationships in the overall ecosystem.	Strategic thinking The ability to collectively develop a plan, design potential interventions, and consider alternatives that could lead to innovation in addressing present day challenges.

Figure 2.2. Ways of thinking grid as shown to participants.

Data Analysis

The qualitative data analysis followed an inductive approach outlined by Miles, Huberman, and Saldaña (2014) and was informed by the SEFT framework. In the first cycle, one member of the team identified data units for analysis if they pertained to either meaning, process, or specific examples of particular ways of thinking as described by the participants. Statements where participating dyads talked about barriers that prevented them from engaging in a particular way of thinking were also included. These data units were extracted and saved in a separate spreadsheet where they were open-coded using in-vivo codes (Tracy, 2013).

The constant comparative method was used during the secondary-cycle to develop a common set of repeated themes for each specific way of thinking from the in-vivo codes (Corbin & Strauss, 2015). The coding scheme was reviewed by the other two members of the research team and code definitions were revised where necessary. Codes were merged or expanded to finally yield major themes of interest. Any discrepancy was resolved by discussion among the research team to reach 100% agreement.

Credibility of interpretations was verified using member-checking (Creswell, 2014). The interviewer frequently summarized statements made by the participants. These statements were used as a form of member checking during the interviews to ensure clarity and understanding. The final results were also shared with five participants for review and comments on accuracy.

Limitations

It is appropriate to recognize the limitations and associated goals of this study before proceeding to the results. First, the study's sample size was small and represents a purposeful sample of engineering and education faculty involved in interdisciplinary research. This initial effort to qualitatively assess ways of thinking was not intended for generalizability. The scope of the qualitative study was intentionally limited to get a preliminary sense and deepen our understanding of the futures, values, systems, and strategic ways of thinking used in EER projects.

Second, the ways of thinking is a complex phenomenon and poses a potential challenge associated with parsing out each of the specific ways of thinking. The research team worked to minimize these concerns as much as possible. For example, the interviews were started with a reflection activity to engage participants in their own thinking prior to showing them the framework. The interviewer referred to specific way of thinking while posing questions.

Finally, the interviews were conducted in a dyad to gather more balanced, complete insights into participants' ways of thinking specifically in the context of their collaborative research projects. Dyadic interviews present many positive attributes but can also lead to a discussion focused primarily on the first thought shared by one member of the dyad (Roulston, 2010). The embedded reflection was used in this fashion to assist in avoiding such an occurrence.

Results

Table 2.2 through Table 2.5 outline the identified themes for each way of thinking with a description of each code and an illustrative text example.

Ways of Thinking Undertaken by Interdisciplinary EER Teams

The following subsection breaks down the results to the first research question – *What do futures, values, systems, and strategic thinking mean in the context of* *engineering education research undertaken by an interdisciplinary engineer education research team?* – for each way of thinking.

Futures thinking. Participants viewed futures thinking as future workforce, broader impact, and imagining changes in existing practices (Table 2.2). Three of the four research dyads (A, C, and D) remarked repeatedly that futures thinking for EER was about preparing students as future engineers and citizens. They talked about teaching students "teamwork," "how to present," "to be an audience member," "to think more analytically and strategically," and "to think deeper" to be better professionals.

There was a sense of futures thinking among participants in terms of seeing the broader impact of their collaborative research. Dyad A anticipated "informing teaching practices" through their interdisciplinary research. Dyad B wanted to "develop educational models that could influence the larger community." Dyad D was "trying to advance state of the art" in engineering education. Dyad B further clarified, "The goal of this was to be thinking of, how can we be impacting the future of education? What are the problems now, what are the problems that are going to persist, and how can we address them?" Dyad C wanted to "reach more learners" in the future to create awareness of sustainability solutions in engineering.

Futures thinking also meant imagining changes in existing educational practices and informing current research designs. For example, Janelle imagined herself teaching meta-cognition to engineers, as "metacognition was not, for instance, a part of their training." She also talked about "how might that look different in engineering education if we paid explicit attention to reading the literature and helping future engineers do that."

Table 2.2

Meaning of Futures Thinking among Participants

Theme	Definition	Subsumed codes	Example
Future Workforce	Preparing students as future successful professionals and citizens	future citizens, changing students' career paths, capturing students' imagination, developing deep thinkers.	"The problem we are trying to address is future workforce, future citizens, energy citizens. We think about it that way, what we are trying to design for."
Impact	Embedding present research within a larger constellation of goals	informing teaching practices, advancing state of the art, solving persistent problems, evidence-based teaching, transportability of outcomes, sustainability of research, reaching more learners.	"We always tried thinking in the future in terms of seeing what your impact is going to be elsewhere. Evidence based teaching, yeah it would have more broad impact and that was always our goal."
Imagining changes	Envisioning future changes in the engineering classroom practices	teaching meta-cognition to engineers, developing educational models, paying explicit attention to literature, future prototypes.	"In terms of the futures thinking we had the participatory design arm, which was really supposed to be about imagining a future and really leveraging what the Center is trying to do."

Overall, futures thinking was less about long-term future, plausible future scenarios, or future generations as envisioned under SEFT; and more about short-term future, making changes one step at a time. Dyad A summed up this notion by stating, "What we think about really is the future in terms of continuous improvement. It is more short-term futures thinking based upon knowledge that you have acquired, which allows you to move forward."

Values thinking. Themes identified under values thinking included diversity and inclusion, user-centered design, value creation through research, motivational values, and collaboration values (Table 2.3). Values of diversity and inclusion were discussed at length by all four dyads. Dyad B talked about diversity being "a big concern" and how they "tried to get diverse voices and representation" in their research. Dyad C mentioned that they were trying to bring in a cultural expert in their interdisciplinary team of content experts and curriculum experts. Kyle explained why diversity was important:

There is different cultural issues, there is different ethical issues with everything you do. So, you need diverse input from different portions of society, people who came from different backgrounds, different genders, different ethnicities, in order to come up with more global solutions as opposed to narrow solutions.

Table 2.3

Meaning of Values Thinking among Participants

Theme	Definition	Subsumed codes	Example
Diversity and inclusion	Recognizing the importance and lack of awareness in the field for diversity and inclusion	understanding affordances and constraints, what it means, access, need to define, diverse voices and representation, create awareness, flexibility, realization of differences, inclusive pedagogies.	"…when we actually sit down with the applications, we find that we have different ways of thinking about diversity, what it means, what we're trying to do with it."
User centered design	Considering values of cultural context and heterogeneity among users when designing a solution	consideration of culture, recognition of heterogeneity, engaging in conversations, diverse inputs, global solutions, flexible solutions.	"In terms of values thinking, I would say that maybe it is the least developed part, but it does map to, I think in some ways reading this, to user-centered design. We're deeply trying to understand our user and our user was a student, and integrate that into the solution."
Value creation	Creating or adding value through collaborative research	research contribution, framing of the problem, application beyond the usual spectrum, cutting the path.	"Each discipline comes from its own values, what is considered a contribution. How do you put together a project where each of those values are represented?"
Motivational values	Integrating personal beliefs and values with engineering education projects	evolving as a professional, making a difference, new learnings, expanding content base, helping students, a sense of mission, satisfaction, opening new horizons, chance to work with students, broadening interest.	"It is really motivation, because you realize that you are changing people's lives. Engineers want to create things that change people's lives. But here, we want to change people's lives through the way we educate them."
Collaboration values	Concentrating on personal values within an interdisciplinary collaborative partnership	complementary expertise, increased chances of funding, functional team, trust, mutual benefits, shared vision, personal element, fluidity, openness, respect, mutual influence, confluence, support.	"I look for three things. The first is a shared vision. We have to want to get to the same place [...] The second one is complementary and non-overlapping expertise and capabilities. The third one is shared benefits, which means that if one of us wins, both of us wins."

Participants also recognized that to act upon values of diversity and inclusion was not easy. During the process of recruiting a diverse cohort of participants, Dyad D realized that their larger team "struggled to think about what diversity means" and they had to "wrestle the conversations." Dyad A also admitted, "We had to compromise because when you have all these people in the room and they are participating in a grant and you are not telling them but what they are hearing is, everything they have ever done is wrong, that is what they are hearing." Overall, while the values of diversity and inclusion resonated with all dyads, participants also indicated a need to create a larger awareness within the profession and further understand the associated benefits and challenges.

Consideration of culture with user-centered design was another common thought in participants' descriptions of values thinking. "Bringing what the user cares about into the design and really taking the user's culture into account" was deemed an important values way of thinking for Dyad B. Kyle explained how in engineering, "there is one best solution but there isn't a best solution, there is a better solution for this segment, there is a better solution for this segment. So, you have got to have some flexibility in your solutions. It is no absolute solution." User-centered design was another area where participants indicated a need for more conversations in the field.

Values thinking was also interpreted as "value in terms of good research" by the participants. Betty explained, "There is a real framing difference when you collaborate and the kinds of questions you ask are really, really different. The instruments you choose and the outcomes are really different." While most of the participants seemed to suggest that their interdisciplinary collaboration was a value addition, Wendy pointed out:

> Different disciplines have sort of different values about what counts as research. You could feasibly write an engineering paper about how you built this thing without talking about the learning results that came out of it. And so I think that is an important part so that to make a good collaborative process, the people

> feel like they are contributing but also getting something back out of it. And not contributing just for the sake of the other person's efforts.

Participants further discussed personal values that influenced their decisions to pursue interdisciplinary engineering education collaborations. Their motivational values included “a sense of mission,” “high level of satisfaction,” “broader interest,” “new learnings,” and “a chance to work with students.” Dyad D also mentioned the desire to “evolve as a professional,” “make a difference,” “expand content base,” “help students,” “open new horizons”, and “create well rounded students” as “there is a lot more than the ability to go in the lab and do experiments, which we often assume is the case about engineers.”

All four dyads discussed values they seek in an interdisciplinary collaboration. The most important value in a collaborative partnership was “complementary expertise.” Henry explained that in building a team, he looks for “complementary and non-overlapping expertise and capabilities. That is why Janelle and I make a good functional team. We definitely need each other.” Participants also mentioned trust, mutual benefits, shared vision, personal relationship angle, mutual ideas, fluidity, openness, respect, mutual influence, confluence, and increased chances of funding as other characteristics they value in a collaboration.

In sum, values thinking resonated with participants and seemed pertinent to their collaborative efforts. The interpretation was different from the original definition provided under the SEFT considering social justice, equity, and ethics. Participants’ conceptualizations also covered a broader spectrum of personal values and valuable contributions of research.

Systems thinking. Systems thinking, for the participants, translated into ‘a holistic product’ and ‘linkages between various parts’ (Table 2.4). Henry explained, “Students, as the product and what it means to be a holistic product, is part of our systems thinking and how we designed the program.” Dyad A also discussed a holistic product, but envisioned the product as a well-structured proposal or a complete story in a journal article. Betty explained:

> When you write grants, you have to apply systems thinking. That is what it is essentially about. You've got a problem, how are you going to solve it, understand it analyze and think about all of the inner…You can't write a successful proposal nor can you write a successful manuscript unless that structure is there.

Systems thinking also meant connecting different parts of a project to create a well-integrated product. Dyad D talked about considering the interdependencies and interrelationships among labs and projects “so students could speak to each other back and forth across their projects”. Dyad B also interpreted systems thinking with connecting different elements of the project together. Retrospectively they mentioned, “we should have synthesized different pieces at multiple points during the effort.” The notion of connecting various parts carried over to the grant and manuscript writing processes for Dyad A, “We'll look at and attack and discuss different parts of a proposal and improve each part. Then, when you change one part, you have to change another.”

Systems thinking was the least developed way of thinking across all four dyads. The examples provided by the participants captured systems thinking at the local, project, or proposal level, but they failed to convey the broader systems thinking that includes K-14 feeders, international students, industry, accreditation agencies, and feedback loops in the overall ecosystem of engineering education.

Table 2.4

Meaning of Systems Thinking among Participants

Theme	Definition	Subsumed codes	Example
Holistic product	Thinking about creating an aggregate product	fit among pieces, synthesis, alignment.	"Students, as the product and what it means to be a holistic product, is part of our systems thinking and how we designed the program."
Linkages	Considering interrelationships of parts and linking various elements of the system	interdependencies, linkages, linking different parts.	"One of the ways we thought we used systems thinking was to think about the linkages between the projects that we were defining, both in terms of the different labs that were represented and how it would affect those labs in our larger Center community."

Strategic thinking. Strategic thinking captured the ideas of creative problem-solving strategies, consensus building with stakeholders, and converting other ways of thinking into action (Table 2.5). Participants' strategic approaches for problem solving included considering alternative educational models, questioning each other's disciplinary assumptions, looking at diverse solutions, designing iterations, contemplating the role of prototypes, understanding objectives, and appending the scientific process of research with communication. Kyle explained why strategic thinking is important:

> In science there might be kind of a single answer for things at that point in time. But in engineering, you try to come up with diverse solutions that address the same problem and then assess the quality of the solution in an analytical way … we're using the scientific method in a different way, because we're looking at creating different approaches to things that have been done before.

Communication with stakeholders was part of participants' strategic thinking, whether for consensus building or for dissemination of completed research. Laura mentioned, "We have so many different audiences. We have to pull the information and describe it in a way that can be understood by different audiences." Dyads A and D included communication as part of a broader theme of strategic thinking being crucial to any research process. This is what Dyad D was trying to give to their students, "the ability to think strategically the process of defining the problem or hypothesis, generating an experimental plan, executing that experiment and communicating the ideas with others."

Table 2.5

Meaning of Strategic Thinking among Participants

Theme	Definition	Subsumed codes	Example
Creative problem solving	Providing examples of strategic thinking approaches for engineering education problems and solutions	scientific process linked with communication process, considering alternative educational models, questioning assumptions, diverse solutions, different approaches, understanding objectives, design iterations, role of prototypes.	"That is about the research process and the scientific process and it is basically strategic thinking. It is the process of defining the problem or hypothesis, generating an experimental plan, executing that experiment, analyzing, that process linked with the communication process of communicating with yourself and with others."
Communication with stakeholders	Strategically communicating with various audiences	stakeholder involvement, dissemination of research, aligning approaches, cater to different audiences, story-telling, nurturing partnerships.	"We are also thinking strategically about the, about passing on our understandings we are gaining through this experience."
Converting other ways of thinking into action	Developing a strategic plan of action to realize other ways of thinking and achieve the desired goals	laying the blueprint, planning the grant-writing process, plan of action, outcomes and evaluation.	"Whether you are an engineer or educator, it turns out the circle of interesting problems is huge and you have to have some way of figuring out which ones you want to work on. It is better if you can find the subset within the important problems. The ones that not only tickle your brain, but if you do something that matters."

Strategic thinking was also about developing a plan to act upon other ways of thinking and achieve the desired goals. For instance, Henry said, strategic thinking is "a way of defining value and determining, which problems to work on." For others, strategic thinking tied with systems thinking. Strategic thinking was a "systematic way of gathering what evidence we already have" and looking at the outcome-evaluation feedback loop. Kelly summed it up for all when she said, "It's helped me set the blueprint for how I think, how I want my research to be conducted."

Overall, strategic thinking captured the focus of all teams' work, connecting futures and systems thinking into feasible actions. Strategic thinking was easily associated with management of resources and logistics, but also signified the grant-writing process, opportunistic approaches for innovation, and importance of communication.

Implementation and Application of Ways of Thinking

The following subsection breaks down the results to the second research question – *How are these ways of thinking implemented and applied by the researcher team?* – for each way of thinking.

Futures thinking. Futures thinking was applied by participants in writing proposals and to some extent designing their projects or programs. For example, Dyad A utilized futures thinking to write "proposals that were transportable and sustainable." That is, the proposals they wrote "represented a model that could be applied in many different settings and could be used by other institutions" and the work "would continue to be sustained into the future, even after the funding had expired." Dyad B conducted a participatory pre-study to imagine the future and used the findings to inform their research design. Dyad D applied futures thinking to design the summer research experience program within their ERC to "capture a few people's imagination and change their career and educational paths." Henry explained, "When we think about future, we're thinking of our product as people, not as the research." Kelly mentioned incorporating futures thinking in her classes when she said, “I don't think, without this collaboration, I would be incorporating so much futures thinking or future-focused activities into my classes. So I do... With every class, there are some activities where I ask them to imagine a future and think about a prototype 50 years into the future.”

Values thinking. Each of the dyads discussed ways in which they implement and apply values thinking. Dyad D provided two examples. First, they described in detail, how they “were looking particularly at the diversity and access to recruit a diverse cohort” and “to provide experience for students who wouldn't otherwise have access to that experience.” They also explained that they saw what they were doing as “educational research on top of engineering research” to “understand the affordances and constraints of that kind of a diverse cohort.” Dyad C customized a few slides of their instructional module to engage “Native American tribes, reaching them through different storytelling or some other method. Teaching the content, but also having it culturally based.” Dyad B admitted that values thinking, “maybe is the least developed part, but it does map to, to user-centered design. We're deeply trying to understand our user and our user was a student and integrate that into the solution.” Dyad A talked about their use of inclusive pedagogies and gender neutral examples of musical instruments or prosthetics in engineering classrooms as a way of applying values thinking. They also noted that values thinking was difficult to implement due to challenges related to “people’s assumptions” and “implicit biases.” Kyle explained, “It's difficult in engineering to create an awareness and a realization that you're not dealing with a homogenous group of people.” Betty added, “I think it's partly what gets funded, partly people's assumption that they have no biases. Everybody has biases. We've worked around the edges of this but it's difficult to get that to be a main thrust I think."

Systems thinking. Systems thinking was either a pervasive component of the collaborative work with varied examples or completely absent from a particular project. As mentioned earlier, Dyad A applied systems thinking to link various parts of the proposals, to compose journal articles, and to create a coherent structure:

> It was much more of a systems proposal because you're linking different parts of the proposal together. What's being done, what isn't being done, what we want to do, how we assess it and what our measurable objectives are, what our evaluation scheme is going to bring forward. So all of these things tied together as a system.

Dyad A also described how they teach systems thinking to students, "when we are building a component, we try to decompose the problem into individual parts, which [they] then reassemble together in optimum form."

Dyad D implemented systems thinking "to consider the interdependencies and interrelationships among members of [their] diverse summer cohort, the participants and their mentors" and "to use those relationships to catalyze learning for all." Henry explained, how participants were paired up, "working on different aspects of the project but they need each other to succeed" and then pairs of students were coupled with a mentor "considering how different projects and labs cohered to affect our community."

Though Dyads A and D mentioned benefits of utilizing systems thinking, Dyads B and C recognized the lack of systems thinking in their work. Kelly said, "Where we really faltered was in systems thinking, because we never quite brought everything, all the different elements of the project together." The three main components of the project "failed to inform and learn from each other's findings for further research and development."

Strategic thinking. The most common example of application of strategic thinking was in the grant writing process. According to Dyad C, “This is a lot of the actual grant writing part, figuring out how we're going to make that plan, and who is going to lead each part, and coming up with basically a strategy for the entire grant.” Strategic thinking was also used for publication planning. Dyad C talked about thinking strategically next time around to make the synthesis actionable, “to account for the natural inflow and outflow of students in the research process” and “to set up explicit channels of communication” among various stakeholders. There wasn’t much variety in the implementation beyond simply using strategic thinking to discern logistics of time, talent, and budget.

Challenges of Implementing Ways of Thinking

Participants also identified challenges associated with implementation, while describing how they applied futures, values, systems, and strategic thinking in their collaborative research. For example, Kyle conceded that futures thinking “was harder to conceive unless you are a soothsayer to look at the future” as “you're always thinking more short-term future than dramatically long-term future.” For Kelly, to “synthesize the different pieces at multiple points while [a system] was in process” posed a challenge. She also described the challenge of working across disciplines:

> Everybody is bringing in their own disciplinary perspective and methods and vocabulary. And then you try to communicate, and the challenge is finding the connection points and the compromises between my objectives and what I think is the right way to do things and the right aims are, and everybody else's objectives ... So it is very much this negotiation between different disciplinary perspectives, if you can even manage to communicate your perspective at all.

The remaining three dyads also conveyed that “learning a new vocabulary, in a very literal sense and also a figurative sense” was a challenge.

Values thinking was identified by all four dyads as the most difficult to implement due to challenges related to implicit biases, assumptions, and embedded culture. Dyad A described the challenge: “The sticking point and it is not just with, it is not him but it is some segment of the engineering culture and as it values ethical thinking, under-representation, understanding whether it fits the culture. That has been a little tough.” Talking about culture, Dyad B described the challenge, “That was a conversation that had to get wrestled down and that we were all committed to serving a diverse cohort but what it looks like, we had to define.” Overall, the challenges indicate that the culture within the field and epistemological differences between collaborators influence how ways of thinking are implemented.

Discussion

We had two primary goals for the current research: a) to provide an appreciation for ways of thinking perspectives with a theoretical background as applied to EER, and b) to provide experimental validity of perspectives through authentic examples. An adapted version of the ways of thinking perspectives, including futures, values, systems, and strategic thinking from the field of ESER, was used given the lack of a cohesive framework in engineering education literature. We discussed their relevance for EER reviewing a breadth of literature. Next, we attempted to get feedback on the pertinence and applicability of these ways of thinking in the context of four interdisciplinary EER collaborations.

The results within the limited experimental scope affirm the relevance of futures, values, systems, and strategic thinking for EER. Findings on futures thinking suggest that while the researchers are rightfully thinking about the future workforce, their anticipatory research approaches are built more on short-term thinking. The results highlight the need for creative thinking that ensures long-term sustainability of successful interventions and alliances that effect system wide adoption of best practices.

Values thinking, while acknowledged by participants as relevant to the field, diverged in meaning and adoption. Prior research has indicated a sense of ambiguity in the field regarding goals, identity, and support mechanisms (Haghighi, 2005; Heywood, 2014; Jesiek et al., 2009). While the field has made progress to clarify its goals and objectives (JEE 2006; Johri & Olds, 2014), we have yet to define the values that inform the field's identity and supporting infrastructures.

Regarding systems thinking, McKenna et al. (2014) wrote, “As a community we are collectively thinking more at the local level than the system level” (p. 189). Results of our qualitative inquiry confirm weakness in engaging with systems thinking. Participants’ examples of systems thinking indicate the importance of linking all elements but lack the scoping of problems and solutions in a larger context. Participants’ conceptualizations were less depictive of the systems thinking regarding broader problem-solving and informed decision-making from the “30,000-foot” perspective. The lack of systems thinking examples from Dyads B and C strengthen our argument for exploring and using ways of thinking in practice beyond recognizing them as a theoretical concept.

Outcomes on strategic thinking indicate participants’ considerations on creative and strategic approaches of problem solving, communication with stakeholders, and most importantly, combining strategic thinking with other ways of thinking for laying the blue-print for a plan of action. Additionally, the challenges described by participants indicate that the implementation of ways of thinking is highly influenced by the embedded culture. This confirms the need for an inquiry that is a deep examination of our own ways of thinking about engineering education and research.

Participating dyads indicated that the ways of thinking framework could be valuable, as it represents “things that collectively an interdisciplinary team should strive to achieve or brainstorm under.” Kelly even went on to mention that their “collaboration would have been more effective if [they] had this framework.” We should not at this juncture make any assumptions about the validity or applicability of these ways of thinking across all levels or projects. We foresee futures, values, systems, and strategic thinking as being four essential compartments of a researcher’s toolkit when it comes to having a structured knowledge base and skillset. The integration of the four ways of thinking build capacity for researchers to situate their projects considering the: 1) complex, intertwined nature of the broad system, 2) long-term, high impact on the field, 3) value addition of their work, and 4) effective, yet realistic implementation. The four ways of thinking become especially suitable for interdisciplinary collaborations where meaning-making takes precedence as researchers share their domain-specific expertise, interpret multiple perspectives, and decide on strategies to address issues at hand (McKenna et al, 2009).

Equipping the engineering education system for 21st century challenges is of paramount importance, not only in the United States, but across the world (ASEE, 2014; NAE, 2004; UNESCO, 2012). The system needs a fundamental shift and transformation through pertinent research and innovative practices (Jamieson & Lohmann, 2012; NRC, 2017). The application of futures, values, systems, and strategic thinking together has great potential to be an important tool for researchers to be able to conceptualize and address a particular situation through a problem/solution pattern that may exist at a variety of temporal and spatial scales in the engineering education system.

Future Work

We plan to build on the promising results presented in this paper to extend this investigation to a larger number of participants involving other engineering education projects at different sites. Related observational data and interview data, will be useful to enhance our understanding of the ways of thinking phenomenon and provide additional validity to the findings presented in this study. We are also considering an open-ended survey with a larger population of NSF awardees involved in interdisciplinary engineering education projects. Future research could also explore additional ways of thinking that might be pertinent to EER (e.g., design thinking or entrepreneurial thinking).

Implications

The implications of this research extend beyond EER, including classroom practices and policymaking. First, the integration of futures, values, systems, and strategic thinking provides organizing principles for collaborators to re-conceptualize and situate their proposals for a larger overall impact in the field. The abilities listed under each way of thinking could be especially helpful to engineering and education faculty members who are planning to collaborate. Second, there is a direct link to engineering classrooms. New skill sets and related thinking abilities required from future engineers to solve sociotechnical, interdisciplinary problems pose a pedagogical challenge for engineering faculty. The ways of thinking discussed here could also provide guidance for engineering faculty to prepare their students. Third, identifying ways of thinking that contribute to the success of EER projects could guide the decision-making for policymakers and funding agencies. An understanding of how engineering education researchers think regarding the needed transformation in the system could be helpful in setting the future direction of proposal calls. Finally, the current line of research has the potential to provide valuable insight into real-world interdisciplinary projects that can be relevant in different settings.

Conclusion

This study represents the beginning of a scholarly exploration on ways of thinking for EER. The challenges faced by the engineering education system are multifaceted and could use novel ways of thinking to address complex problems (Adams et al., 2011; Donofrio & Whitefoot, 2015; Jeseik et al., 2009). The overarching goal of this exploratory work is to initiate a vision of a *ways of thinking* framework that goes beyond the status quo in addressing a particular problem through new, interdisciplinary insights. The ways of thinking presented here build capacity for all stakeholders to explore whether it is possible to teach engineering in a different way, to bring institutional change, and to create an innovative and inclusive profession.

CHAPTER 3

WAYS OF THINKING: A QUALITATIVE INQUIRY

This chapter presents the second of three studies. The second study builds on the theoretical foundation and preliminary results presented in the previous chapter. It details an empirical inquiry that qualitatively examined ways of thinking among engineering and social sciences researchers who collaborated for interdisciplinary research. The study specifically examined what and how researchers who work on engineering education projects think and do about futures, values, systems, and strategic thinking.

Data sources included dyadic interviews and observations of team meetings. Interview data was analyzed for themes which were enjoined with the ways of thinking concepts. Observational data was used for triangulation. The results include: 1) conceptualizations of futures, values, systems, and strategic thinking among participating researchers, 2) authentic examples of applications and implementation of the four ways of thinking in engineering education research, and 3) challenges of implementing different ways of thinking. Overall, the results suggest the presence of short-term futures thinking, varied interpretations of values thinking, weaknesses in broader systems thinking, and a strong focus on strategic thinking. The results of this study are intended to inform the design of an original survey instrument to further explore the underlying dimensions of futures, values, systems, and strategic thinking (see Chapter 4).

It should be noted that this chapter is written as a manuscript for potential publication in the *Journal of Engineering Education*. As a result, readers may note passive voice in the writing as well as references to terminology such as “this paper” or “emerging themes.” Readers may also notice redefining of abbreviations and citations.

Introduction

'You don't start from I want to do this activity,' said Douglas. 'You start from I want to make this cultural change. That's a very different way of thinking…'Let's think about how to not just cross-fertilize but cross-collaborate and create these larger partnerships that can work more broadly and at a larger scale to impact the engineering education field. What we want is broad, radical change in engineering education.'

Engineering Societies and Undergraduate Engineering Education: Proceedings of a Workshop

(Olson, 2018, p.8)

Sharing his thoughts, Elliot Douglas, former National Science Foundation (NSF) program director within the Division of Engineering Education & Centers, exemplifies the importance and influence of ways of thinking on engineering education. The importance of ways of thinking has led to many studies examining the same among engineering students (Chen, & Levinson, 2006; Keltikangas & Martinsuo, 2009; Lumsdaine, E., & Lumsdain, M., 1995; Moore & Hjalmarson, 2010) with little focus on engineering education researchers' ways of thinking and the influence on their decision-making. Numerous indirect mentions of ways of thinking can be found in the literature. For example, a study examining cross-disciplinary collaborations acknowledged different ways of thinking across disciplines (Borrego & Newswander, 2008). A case study of gender issues among science faculty indicated that women have different ways of thinking about academic research and teaching (Viefers, Christie, & Ferdos, 2006). Adams et al. (2011) showed the use of a multiple perspectives methodology to challenge assumptions and ways of thinking among scholars. Case and Light (2011) called for "research studies that are able to go beneath the surface of common sense ways of thinking about engineering education" (p. 190).

This research effort aims to directly address this knowledge gap regarding ways of thinking among engineering education researchers. The current exploratory study used an interpretive research approach to examine ways of thinking, specifically among engineering and social sciences researchers who collaborated for engineering education research (EER). The study uses the Sustainability Education Framework for Teachers (SEFT) as a guiding framework. The SEFT considers complex educational problems and solutions through four specific ways of thinking: 1) futures, 2) values, 3) systems, and 4) strategic thinking (Warren, Archambault, & Foley, 2014).

This paper describes the framework detailing futures, values, systems, and strategic thinking, research design and methodology, and emergent findings. The results present an overview of the themes identified using a qualitative analysis approach along with "thick descriptions" (Geertz, 1973) from the data to illustrate detailed and contextualized perspectives of different ways of thinking among researchers. The results are then discussed in the context of current challenges in EER and potential use in informing future research practices. A work in progress version was previously presented at the 2018 Annual Conference for the American Society for Engineering Education (ASEE) (Dalal & Carberry, 2018).

Ways of Thinking

Ways of thinking refers to a viewpoint or a perspective. The term *ways of thinking* is often theoretically associated with a systematic thought process or reasoning that informs an action (Sousa, 2016); it is a set of principles or ideas used to find an answer to a question. Many fields have defined ways of thinking in a way that is meaningful to the field. The learning sciences defines ways of thinking as an approach to solving complex problems through coherent patterns in reasoning (Harel & Sowder, 2005). Business and finance view ways of thinking as an intuition of pattern recognition combined with anti-intuitive rigorous rules that inform decisions and judgements (Douglas, 2000).

Regardless of how ways of thinking is defined, it should be noted that ways of thinking is not a heuristic. It is a set of principles for examining and considering problem/solution constellations in a coherent fashion. Different ways of thinking facilitate different strategies and ideas for innovation, and influence subsequent actions to address diverse educational challenges. Accordingly, Warren et al. (2014) proposed a ways of thinking framework that embraces four ways of thinking – futures, values, systems, and strategic thinking – to tackle complex challenges in sustainability education.

Guiding Framework

As an emerging and inherently interdisciplinary field, EER has frequently drawn on lessons learned from other fields (Borrego & Newswander, 2008; Fortenberry, 2014). This study takes insights from the Environmental and Sustainability Education Research (ESER), a similarly emerging and interdisciplinary field that aims to solve common societal problems through education. The current study uses an adapted SEFT to understand ways of thinking as a lens for considering and addressing complex challenges (Warren et al., 2014). As mentioned earlier, the SEFT articulates concrete abilities for four specific ways of thinking: 1) futures, 2) values, 3) systems, and 4) strategic thinking (Warren et al., 2014). The combination of these four ways of thinking present a networked approach for considering complex problems and solutions (Figure 2.1).

Futures thinking involves exploring the present with anticipatory approaches to understand and prepare for future changes, problems, and solutions. *Values thinking* concerns the integration of justice, equity, and ethics in designing a solution. *Systems thinking* is about considering holistic approaches to problem-solving that understand and analyze the complexity of various elements and their interrelationships in the larger ecosystem. *Strategic thinking* involves the ability to collectively develop a plan, design potential interventions, and consider possible alternatives that could lead to innovation in addressing today's challenges (Warren et al., 2014).

These four ways of thinking offer key insights into knowledge, skills, and attitudes necessary for solving challenges with regard to education. The framework presents organizing principles for questioning, researching, and reflecting in interdisciplinary situations. The present study uses this framework as a guiding lens to explore embodiments of engineering education researchers' ways of thinking. Examining conceptualizations of futures, values, systems, and strategic thinking in the context of interdisciplinary engineering education projects, the current study illustrates how particular ways of thinking influence researchers' decisions and plans to address engineering education challenges.

Futures, values, systems, and strategic thinking are interconnected. When used in conjunction, these ways of thinking link seemingly disparate topics that have been and become the problem of engineering education, such as diversity and inclusion in the system, disjuncture between research and practice, or sustainability of the planet (Finelli, Daly, & Richardson, 2014; McKenna, Dalal, Anderson, & Ta, 2018; Guston, 2013). The four ways of thinking when united, build capacity for researchers and practitioners alike to be able to understand the broad and complex nature of engineering education challenges, conceptualize future-oriented solution driven studies, and create long lasting value for the field. Together they present a networked approach that could bring transformational change in engineering education. In the following sub-sections each way of thinking is described in further detail.

Futures Thinking

Futures thinking is anticipatory thinking. It involves changing the nature of present day decision-making to consider and address tomorrow's problems (Warren et al., 2014). Futures thinking is not about forecasting or predicting. It is a "navigational tool" to: 1) adaptively prepare for future changes, problems, and solutions, and 2) envision plausible future scenarios to create bold new paradigms for preferred futures (Miller, 2003; NAE, 2004; OECD, 2017). Futures thinking entails the ability to accept uncertainty, consider diverse interdisciplinary perspectives, connect present-day research findings to identify emerging issues, potential threats, possible outcomes, and opportunities, and ultimately create new approaches (processes, strategies, and models) to bring about profound change (Daanen & Facer, 2007; NAS, 2007; Warren et al., 2014). As the Engineer of 2020 project (NAE, 2005) demonstrated, futures thinking is about pro-actively envisioning the roles that engineers will play in the future and anticipating where engineering education needs to go and how it will get there.

Values Thinking

Values thinking is also known as ethical thinking, normative thinking, or value-focused thinking (Warren et al., 2014). Values are basic convictions about right or wrong, good or bad, and desirable or undesirable. However, values thinking is less concerned with moral values. Instead, it is about social-humanistic research and reflexivity that recognize the concepts of ethics, equity, and social justice in the context of varying cultures and decision making (Sarkikoski, 1988; Vesilind, 1991; Warren et al., 2014; Wiek, Withycombe, Redman, & Mills, 2011b). It entails the ability to include all segments of users when designing solutions, consider the intended and unintended consequences of engineered solutions, and adapt the solutions in an ethical way (Guston, 2003; Wiek, et al., 2011b). As Stilgoe, Owen, & Macnaghten (2013) explain, values thinking is about “holding a mirror up to one’s own activities, commitments and assumptions, being aware of the limits of knowledge and being mindful that a particular framing of an issue may not be universally held” (p. 4). In sum, values thinking is a crucial component of any empirical inquiry that involves an understanding of culture, willingness to interact with all stakeholders, and desire to help humanity and life (NSB, 2007).

Systems Thinking

A system is a bounded entity comprised of multiple elements that function as a whole through an intricate web of interrelationships (Fordoyce, 1988). Systems thinking is the ability to see interdependencies between elements while working with the whole (Godfrey, Crick, & Huang, 2014; Warren et al., 2014), i.e., it’s a holistic approach to problem solving. Systems thinking does not equate to complete knowledge, but instead is the understanding of nonlinear structure and causal loops that are further in time and space and may originate from different organizational scales (Nehdi & Rehan, 2007; Wiek, Withycombe, & Redman, 2011a). Systems thinking also includes the ability to recognize the interrelationships of engineered systems with technical and non-technical systems in other domains that include environmental, economic, or socio-cultural systems (Kellam, Maher, & Peters, 2008). Overall, Systems thinking is about “assessing the degree of system complexity and analyzing system dynamics to make informed decisions that reduce the risk of negative outcomes” (Warren et al., 2014, p. 8).

Strategic Thinking

Strategic thinking is the ability to create a plan of action to achieve the desired vision (Warren et al., 2014). Though it involves envisioning long-term goals and objectives and considering appropriate courses of action to be able to meet specified goals, strategic thinking exceeds planning (Lawrence, 1999). It involves an ability to frame every decision by how it contributes to achieving a particular vision while critically thinking about consequences, implications, and indirect effects, considering the larger context (Warren et al., 2014). It is a creative, divergent process that involves challenging existing assumptions and the status-quo to come up with alternative viable strategies or models that deliver value (Abraham, 2005). Strategic thinking is future-oriented, but it is distinct from futures thinking. Futures thinking typically involves imagining a most likely future and working backwards to prepare for anticipated changes, whereas strategic thinking involves the ability to respond promptly and effectively to unforeseen circumstances. Strategic thinking is where the abilities that comprise systems and futures thinking are translated into action to deliver value (Wiek et al., 2011b).

Research Questions and Significance

The NSF promotes interdisciplinary collaborations between and among engineering and social sciences faculty to bring novel ways of thinking in the existing research practices (NSF, 2017; Wankat, Felder, Smith, & Oreovicz, 2002). To explore what emerges in the specific ways of thinking among collaborating researchers, especially in the context of authentic EER projects, the following research questions were developed and examined:

1. How do researchers participating in engineering-social sciences interdisciplinary collaborations conceptualize each of the ways of thinking, including futures, values, systems and strategic thinking?
2. How are futures, values, systems, and strategic thinking implemented by collaborating engineering and social sciences researchers in their engineering education projects?
3. What are the challenges for collaborating engineering and social sciences researchers in implementing futures, values, systems, and strategic thinking?

The contribution of this study is three-fold: 1) appreciation for novel ways of thinking as conceptualized in ESER under the SEFT, 2) experimental evidence regarding ways of thinking perspectives within authentic projects, and 3) foundational work to initiate a vision of an EER ways of thinking framework.

This study is not an introduction of futures, values, systems, and strategic ways of thinking to the field. The contribution is the integrated approach that combines these four ways of thinking as part of a researcher’s toolkit to question, reflect, and address complex issues. A model combining these ways of thinking has the potential to serve as an organizing and motivating structure to frame decisions throughout all engineering education endeavors. This exploration conceptualizes and implements specific ways of thinking across a variety of projects to illustrate how collaborating researchers think, act, and engage with their engineering education inquiries. The study contributes to the field by showing that *ways of thinking*, while perceived as a concept in theory, can and should be used in practice to innovate. The result, is the beginning of a foundation for a future EER ways of thinking framework.

Research Design

A qualitative research design was used to explore ways of thinking between and among a select group of engineering and social sciences researchers who collaborated for engineering education projects at a doctoral university with very high research activity in the United States (The Carnegie Classification, n.d.). The study followed an interpretivist theoretical framework with constructivist epistemology, which acknowledges subjectivism and contextualism (Flick, 2014). In the constructivist paradigm, while the data come from the participant's experiences, the researcher uncovers valuable interpretations and the knowledge is constructed from the point of view of those who live it (Koro-Ljungberg, Yendol-Hoppey, Smith, & Hayes, 2009). The findings do not reveal ultimate truth (Crotty, 2003). A discussion of study participants, data collection procedures, and analysis is presented next.

Participants

To explore ways of thinking, 12 engineer-social scientist collaborator pairs, were identified using maximum variation purposeful sampling (Creswell, 2013). The intent behind purposeful sampling is to gather "thick" data (Geertz, 1973). Within the maximum variation sampling method, the researcher is able to better understand the phenomenon among different people, in different settings, and at different times. It also increases the trustworthiness of the research by collecting diverse data (Creswell, 2013; Gibbs, 2007). Maximum variation sampling considered the context of the collaborations to investigate ways of thinking across heterogonous engineering education projects. Four potential participants declined to participate or were not available within the requested time period. One of them suggested to interview another member of the team instead. Finally, nine engineer-social scientist collaborator pairs (Table 3.1) were interviewed. It should be noted that four of the nine projects had additional members, but the 18 participants were selected for interviews based on their leadership roles.

Table 3.1

Participant Details by Dyads, Projects, and Disciplines

Participants	Project context	Program (engineering/social sciences)
Dyad 1	Undergraduate teaching (UG)	Materials engineering/Education
Dyad 2	Intelligent tutoring system (UG)	Computer engineering/Psychology
Dyad 3	Undergraduate curricula (UG)	Civil engineering/Education
Dyad 4	Engineering faculty development	Biomedical engineering/Education
Dyad 5	Diversity efforts (ERC)	Geotechnical engineering/Psychology
Dyad 6	Summer research experience (ERC)	Electrical engineering/Learning sciences
Dyad 7	Specialty courseware (ERC)	Geotechnical engineering/Education
Dyad 8	High school science textbook (K-12)	Computer science and engineering/Learning sciences
Dyad 9	STEM* Teacher preparation	Mechanical engineering/Education

*STEM: Science, Technology, Engineering, and Mathematics

Data Collection

Data sources included dyadic interviews with engineer-social scientist pairs and observations of team meetings. Dyadic interviews were used because they foster interaction during the interview and expand coverage of the research topic when participants share a preexisting relationship (Morgan, Eliot, Lowe, & Gorman, 2016; Morris, 2001). During dyadic interviews, participants often differentiate their thoughts and talk about ideas that might not have occurred to them individually (Morgan et al., 2016). Considering the collaborative nature of engineering education projects, dyadic interviews made for an appropriate choice to gather comprehensive, balanced insights into participants' ways of thinking. Semi-structured interviews lasting approximately 60 to 90 minutes were designed and implemented to elicit conceptualizations of futures, values, systems, and strategic thinking from the engineer-social scientist teams.

Dyads were first asked to describe their collaborative research. Then they were shown definitions of futures, values, systems, and strategic thinking from the SEFT (Figure 2.2) on four quadrants of a grid on paper as a stimulus (Roulston, 2010). Teams were then prompted to discuss how they conceptualized each of the four ways of thinking for engineering education and research. Teams were asked if these ways of thinking played a part in their collaborative projects and how. Challenges of implementation were also explored.

Observations were an additional data source that were included as a form of triangulation (Creswell, 2013). Six team meetings were observed for two projects over a 14-week period. The observations looked for the presence and specific examples of futures, values, systems, and strategic thinking during team interactions.

Data Analysis

Qualitative data analysis was informed by the SEFT framework in combination with an inductive, two cycle coding approach (Miles, Huberman, & Saldaña, 2014). NVivo 12 was used to facilitate data analysis. In the first cycle, data units were open-coded, often using in-vivo codes, based on the concepts underscored by participants during interviews for each way of thinking (Saldaña, 2009). The iterative process of reading-coding-re-reading continued until coding saturation was reached. The data units were repeatedly read with codes consolidated or expanded as necessary. An initial coding scheme was developed using this process by the first author after analyzing five transcripts. The scheme was reviewed and modified for improved specificity by the research team. The revised coding scheme was applied to recode the initial five transcripts and to code the remaining four transcripts. Recoding was done five weeks after the initial coding to establish trustworthiness in the first author's coding efficacy.

In the second cycle, the constant comparative method (Corbin & Strauss, 2015) was used to develop a common set of repeated themes or axial codes for each way of thinking from the open codes. As an example, when asked about futures thinking, one of the participants said, "I think of futures thinking as a way to identify what problem there is to solve. What are the problems now, what are the problems that are going to persist, and how can we address them?" This data unit was open coded as 'identifying persistent problems' and later merged under the category of 'transformational mechanisms.' The coding trees for each way of thinking that resulted from the two cycles are included in Figure 3.1 through Figure 3.4.

For trustworthiness and rigor, approximately 30% data units under each way of thinking were coded by another member establishing an inter-rater agreement of 82.7%, 84.8%, 90%, and 86.7% for futures, values, systems, and strategic thinking respectively. These values fell within the almost perfect range (.81-1.00) as characterized by Landis and Koch (1977). The two coders met again to resolve the differences and achieve 100% agreement.

It should be noted that due to the highly-correlated nature of the four ways of thinking, some coding labels in the first cycle repeated among different ways of thinking. The distinction was made by reading the statements before and after the data unit in an effort to understand the context. As an example, the code *impact* appears in futures thinking and in values thinking. Under futures thinking, the open code and the theme of "impact" conveyed participants' thinking about broader outcomes of the research in the future. The same code under values thinking suggested that participants see the impact of their research as a value-added contribution. Since semi-structured interviews asked questions referring to each way of thinking, the contexts were clear. There were instances where participants remembered something related to a previously discussed way of thinking and added references to the ongoing discussion. Distinguishing between systems and strategic thinking was particularly challenging when statements such as "we tried to think of strategies in a systematic way" were used. Strategic thinking was interpreted as more about means and actions, while systems thinking focused on the end goal or vision. Data units focused on different domains, structure, components, and showing understanding of inner fabric and dynamics were coded under systems thinking. An example includes, "We need to look at the social impacts too about how what we're doing affects the social fabric." On the other hand, data units focused on actions related to viability, feasibility, efficiency, effectiveness, partnerships, planning, adapting, and understanding of barriers were coded under strategic thinking.

Credibility was ensured by employing triangulation and member checking (Creswell, 2013). Field notes and jottings from the observations were used to triangulate the interview findings. Member checking took place at multiple times to verify interpretations and findings. First, during the interviews the lead researcher often summarized statements made by the participants to ensure understanding. Emails were sent to participants as needed during data analysis to ask for further clarification regarding certain terminology or context. Finally, the thematic results were shared with the participants to preview and comment on.

Limitations

The study used a purposeful sample of engineering and social sciences researchers involved in interdisciplinary research at one institute. The intention was to gain detailed, contextualized perspectives and deep understanding on ways of thinking in participants' actual voices (Flick, 2014). Generalizability is a limitation of such a qualitative inquiry; however, results were not intended to be generalized. To provide transferability, detailed descriptions are used in the results section (Guba, 1981). Researcher's subjectivity (Creswell, 2013) could be a limitation in qualitative research, which is why member-checking was used to evaluate the accuracy of the interpretations and conclusions as described in the earlier section.

Results

Results are presented in three forms for each of the research questions to provide an authentic representation of the ways of thinking under investigation: 1) conceptualizations of futures, values, systems, and strategic thinking (description of each theme together with illustrative text) with narrative explanation; 2) examples of applying and/or implementing ways of thinking described in narrative embedding participant quotations; and 3) "thick descriptions" (Geertz, 1973) from the data illustrating challenges associated with each way of thinking.

Ways of Thinking: Conceptualizations

The following subsections break down the results to the first research question: *How do researchers participating in engineering-social sciences interdisciplinary* *collaborations conceptualize each of the ways of thinking, including futures, values, systems and strategic thinking?*

Futures thinking. Themes that were identified from the iterative interpretation of data on futures thinking centered on engineering education and engineering education research. Table 3.2 provides a summarizing overview of all themes conceptualized under futures thinking by 18 participants.

Themes of *future workforce, content changes*, and *pedagogical changes* conveyed participants' futures thinking about engineering education. These themes hinged on the idea of preparing students as future citizens and professionals by imagining changes in the existing curricula or pedagogy. For one geotechnical engineering faculty, futures thinking was about well-rounded students who knew "about diversity, about being the mentors, about leadership and writing" as she "never acquired them in [her] engineering experience" and "had to learn the hard way." She said, "I had 168 credits and there was no one credit about writing or even there was no one credit on teaching as I went through my PhD program." Another engineering faculty suggested taking a Montessori approach – introducing capstone projects in the first year and building knowledge and skills along the way so you are "starting with concrete materials and then having abstract symbols and then making that connection." Participants also talked about futures changes in pedagogy such as more active learning approaches, teaching metacognition to engineering students, and faculty development as evidenced by the subsumed codes displayed in Figure 3.1.

Table 3.2

Participants' Conceptualizations of Futures Thinking

Theme	Description	Example
Future workforce	Preparing students for future careers and as future citizens	"To me that is what we are all about, educating students so students can go do what they want to do and they are prepared for whatever they want to do in life."
Content changes	Filling curricular gaps in the future with classes and subjects that are not necessarily taught in engineering programs or changing the order in which courses are taught	"This was not being taught at the undergrad level, how to build on unsaturated soils. It was in graduate courses. But many engineers don't go through graduate programs, they don't need a graduate degree. So it wasn't in the curriculum at all. So that was totally sustainability and futures thinking was why we wanted to build that into the undergrad curriculum."
Pedagogical changes	Changing the way engineering faculty teach considering future and current trends	"We have got to change what we have been doing because we have been using the industrial model from the '30's and '40's, that is old-school. And, a lot of our schools are still doing that that old traditional rote memorization and whatever else."
Imagining	Envisioning what education would look like in the future or envisioning a future for self	"We have to look at what 10, 15, 20 years down the line, what is education going to look like? Well, it is going to be dependent on how we train the [students] right now."
Transformational mechanisms	Considering processes that could bring transformational change in the system in the future	"What kind of problems can you try to address through the lens of being an engineer? And so, some of that is, well, there are some things that are obviously within the canon of engineering and some things that, maybe, are a little bit further afield, but one can think creatively of how to use a process to try to address. And so, I think of futures thinking as a way to identify what problem there is to solve, the result being a focused question."
Impact	Embedding present research within a larger constellation of goals for wider adoption or long lasting outcomes in the future	"It is a brand new field and we hope in the 10 years that it becomes a household name that kids think about themselves going to be BioGeo engineers."
Stakeholder support	Thinking about involvement of funding agencies, administrators, and public to adopt outcomes, provide infrastructure, and sustain research in the future	"Designing infrastructure for the faculty, for adoption. There is also a lot of research that shows just because you build it and because it's effective doesn't mean anybody in the world is going to pick it up."
Incremental improvement	Small, cumulative changes considering immediate future	"You are continuously improving, so you are thinking more short-term future than dramatically long-term future."

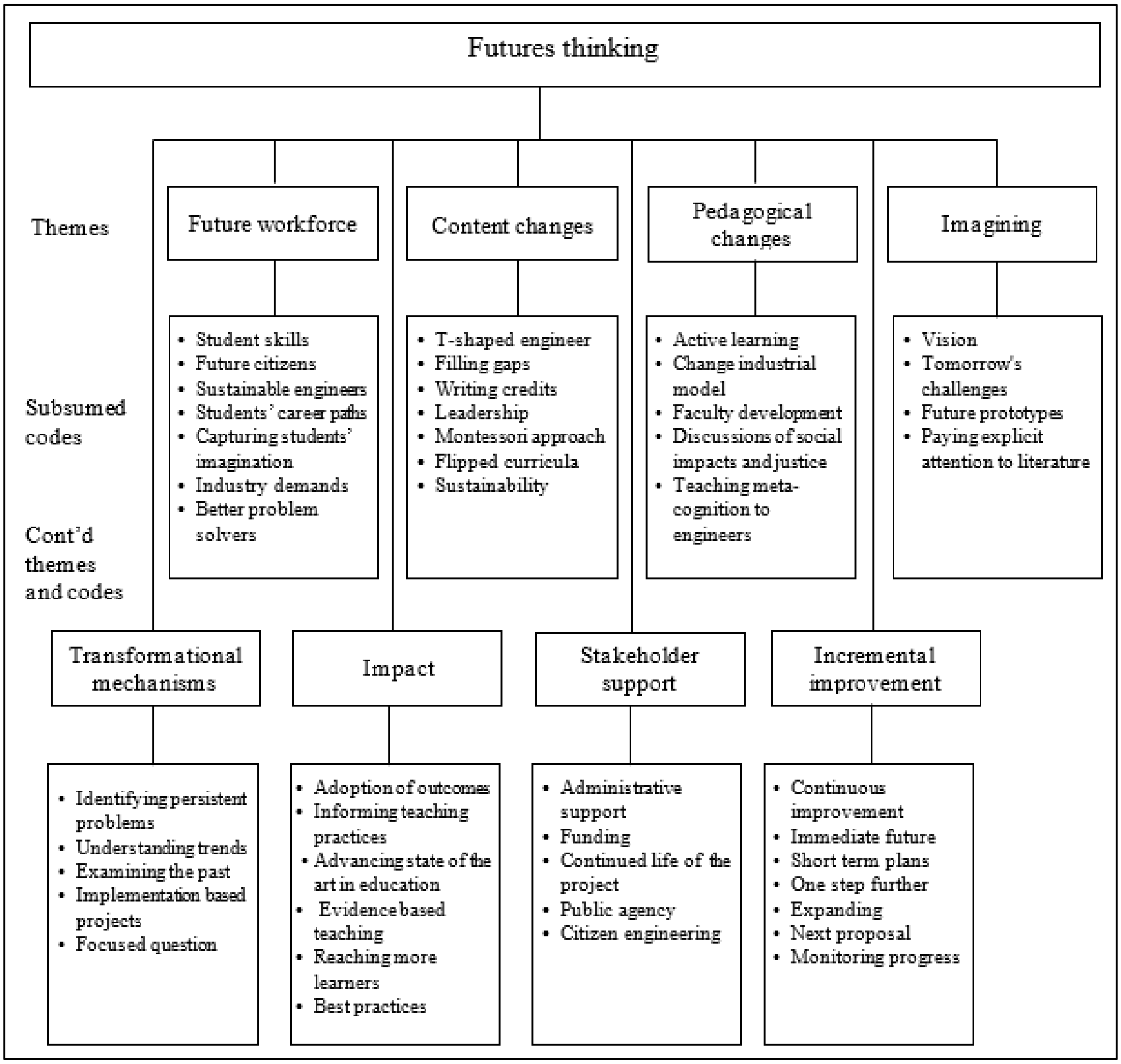

Figure 3.1. Coding tree for futures thinking. Format adapted from Borrego and Newswander, 2008.

Futures thinking also meant *imagining* changes in existing educational practices and informing current research designs. For example, a learning sciences researcher imagined herself teaching metacognition to engineers, as "metacognition was not, for instance, a part of their training." Other themes pertaining to research included *transformational mechanisms*, *impact*, *stakeholder support*, and *incremental change*. There were some references to processes that could bring transformation such as examining trends to identify problems, focusing on research-based implementation projects as opposed to theoretical research, and formulating questions looking into the future. Implications and impact of research to inform teaching practices was one of the leading thoughts considering the future. Four dyads expressed concerns regarding infrastructure for adoption of research in practice or challenges of sustaining projects in the future when the funding expired.

Overall, futures thinking was less about disruption and more about small, continuous improvements. Observations confirmed the theme of *incremental improvement* as team discussions revolved around changes in the next cycle, evaluations, comparisons with past years' results, and sustaining the work through additional grant(s).

Values thinking. Values thinking was acknowledged by participants as relevant to the field, but diverged in meaning and adoption from the original definition of the SEFT. The categories in Table 3.3 convey the broad spectrum of multiple interpretations of values thinking by the participants.

The theme of *research values* contained a number of statements that conveyed participants' thoughts regarding value creation through collaborative research. Some of the subsumed codes of best practices, knowledge creation, impact, or different perspectives (Figure 3.2) indicated the value of research contribution.

Table 3.3

Participants' Conceptualizations of Values Thinking

Theme	Description	Example
Research values	Appreciating research perspectives or outcomes of research as valuable	"There is always the value of discovery, creating new knowledge, knowledge that will ultimately have an impact on society. That is a clear value, I think, that is always expressed, and we are in education so we value knowledge generation."
Pedagogical values	Recognizing learning and instruction related practices and outcomes as valuable	"Values thinking is kind of what is at the core of a lot of the type of pedagogy, you would promote in a project. Being able to be, to collaborate, to work with others, to think on their own and to be perseverant. [And so] that should be promoted within the classes at the beginning of their engineering career."
Design values	Considering the values of context, experience, and heterogeneity of end users when designing a solution	"To me, the more useful thing to impart than the process or the product is the general pedagogical approach, so values with engineering design, design thinking of having students practice problem-solving where they have a basis in empathy for the user."
Personal values	Integrating individual beliefs and values with engineering education projects	"If you feel good about this, if you feel it is inspirational, that it's going to help people, help students learn, help their careers, help their future, help other people teach better and have the students perform better, maybe improve the retention rate, don't go through the experience I did when I was an undergraduate, you are going to put a lot more energy in because you value that so much."
Collaboration values	Concentrating on personal values within an interdisciplinary collaborative partnership	"We are thinking like the fit of a priority scheme, that when I work with people who share my priorities and how will I go about something, why I want go about those things? It works. And I have found that with this group and I have found that with [co-PI name]."
Societal values	Considering social and cultural impacts of work as value generation	"I think one of the values of the ERC is that we are trying to create good citizens. Not just good engineers but good citizens."
Diversity and inclusion	Recognizing the importance and lack of awareness in the field for diversity and inclusion	"To create a more inclusive and diverse workforce, you have to prime the pump, you have to have something in the pipeline, and that is what we haven't had in the past. Unless we reach down to elementary school level and get kids, with a diverse group of people, interested in what we do, we are not going to have a diverse workforce."

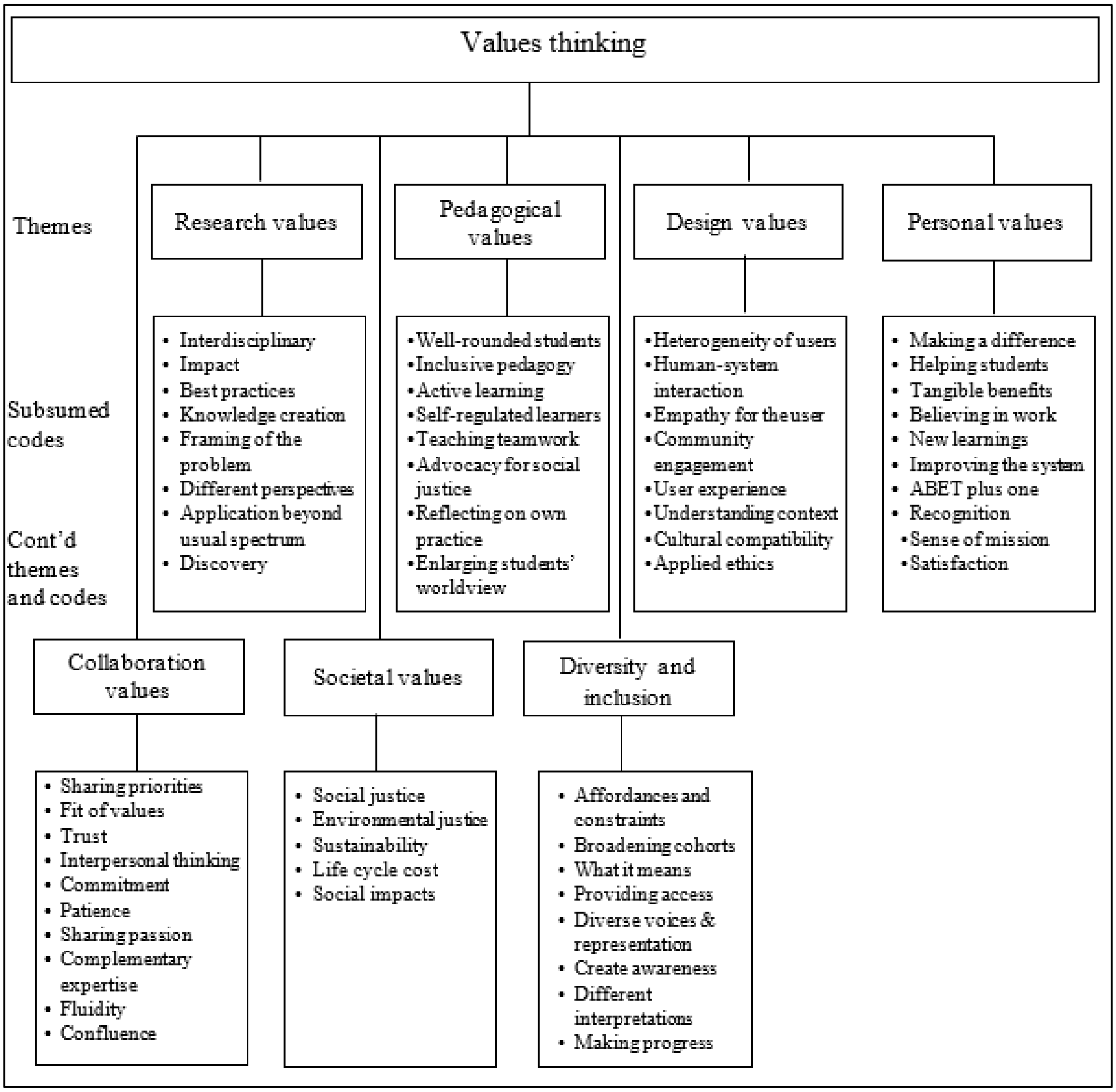

Figure 3.2. Coding tree for values thinking. Format adapted from Borrego and Newswander, 2008.

Pedagogical values described participants' reflections on teaching practices and valued outcomes for student skills. This category somewhat related to the themes of *future workforce* and *pedagogical changes* under futures thinking with open-codes such as self-regulated learners, active learning, teamwork, and awareness of social justice. The high number of subsumed codes for this category indicates that this aspect was relatively significant in participants' thoughts. During team meetings, as participants planned their summer research activities, the focus was on creating value for students. Meeting observations also suggested tension among one particular group because they felt teaching was valued among engineering faculty only because it was tied to year-end evaluations.

A group of values relating to design and design thinking were collated in *design values*. Particularly prominent within this theme were references to heterogeneity of users and culture. Statements such as “some of the early participatory design work, that was a big concern, because it was a very homogenous group” or “when I come up with [an engineering] solution to a problem it has to reflect the culture or the community that I'm dealing with” conveyed design values among participants.

Themes of *personal values*, *collaboration values*, and *societal values* conveyed participants’ values thinking connecting these aspects with their engineering education work. *Personal values* such as making a difference, providing quality education, providing value for students’ money, or improving the system by bringing in evidence-based practices (Figure 3.2) conveyed values thinking regarding individual beliefs. *Collaboration values* reflected professional values of collaboration interspersed with personal core values. This theme contained a relatively large number of statements from the values thinking dataset. For example, one education researcher said, “This collaboration is something that I have continued to seek out. So if I think about my other collaborations, for the most part I prefer to do it in a way that it's mutual, and fluid and very collaborative.” Subsumed under *societal values* were a number of open codes and data units where participants, primarily those who worked in ERC settings, talked about environmental sustainability, social justice, citizen engineering, public agency, and social impacts. A participant mentioned, "Even if it is not technically a new gadget, but a gadget that can be adapted to help a large portion of the population globally […] I think is a value that we can work harder to embed."

Participants' views on prevailing values on diversity and inclusion within engineering departments coalesced around the theme of *diversity and inclusion*. The statements and subsumed codes hinted that there is "recognition over the last couple of decades of the value of inclusion and diversity," but there is further need to create awareness. One engineer explained the need for diversity and inclusion values, "You really need diverse input from different portions of society, people who came from different backgrounds, different genders, different ethnicities, in order to come up with more global solutions as opposed to narrow solutions." The topic of diversity and inclusion frequently came up in one of the ERC's leadership team meetings.

Overall, values thinking resonated with participants and seemed pertinent to their collaborative efforts. Interpretation occurred in multiple ways considering diversity and inclusion, value creation through research, and personal beliefs.

Systems thinking. Data units identified under systems thinking converged on the concepts of *bigger picture, weaving a tapestry,* and *sub-systems and their interactions* (Table 3.4). Statements relating to broader implications, going beyond departmental silos, or creating a holistic product were collated under *bigger picture*. Some of the statements suggested that participants were looking at the bigger picture of the purpose of engineering or engineering education. For example, one participant said, "engineering isn't specifically about workforce development or about invention, right? I mean, it's a way to critically engage in the world."

Table 3.4

Participants' Conceptualizations of Systems Thinking

Theme	Description	Example
Bigger picture	Thinking about implications of the work in a larger context of the whole system	"It was the content areas working together to address one main thing they have in common, which is problem solving and all of these pieces lead to a bigger picture."
Weaving a tapestry	Synthesizing and making connections to integrate different strands of the project	"What are our inputs, what are our goals, what are our activities, who are the participants, and then what are short-term, medium-term, and long-term outcomes? Making those connections from different areas throughout and if that is not systems thinking I don't know what is."
Sub-systems and their interactions	Recognizing of the engineering education system as a configuration of components connected together by a web of relationships.	"I think the part that was missing is the focus on the faculty, which is that there is a second, there is multiple pieces. Let us just take the three pieces that the University directly controls, is the students, the classes, the curriculum, and that is typically what we focused on. There as a University administrator, you can tell the students to do stuff, you can look at what the curriculum is, but very few universities go tell the faculty member 'You need to change how you teach'. If you are thinking this is the system, that is an important piece."

Many statements were reported about integrating different parts of the projects, making connections between inputs and outcomes, synthesizing what was done, and creating synergy between and among different components (Figure 3.3). These converged under the theme of *weaving a tapestry*. It was a prominent theme as many of the statements coded under systems thinking fell under this theme. For example, one dyad talked about how they thought about "the linkages between the projects; how the students could speak to each other across their projects and how those projects together cohered into a set […] to affect the larger center community."

The theme of *sub-systems and interactions* described participants' understanding of feedback loops and intersections among various elements of the system. This was mostly discussed in the context of individual projects. For example, one dyad described their project as situated within the system of "computer architecture […] which includes the hardware that is designed for the computer, but also the software." There were a handful of references that conveyed the recognition of sub-systems (e.g., industry, Accreditation Board for Engineering and Technology (ABET), international students) in the overall engineering ecosystem but in different contexts. For example, the illustrative text included in Table 3.3 that reflects the theme of diversity and inclusion also conveys the recognition of the K-12 system as a major influencer into encouraging students to pursue engineering pathways. One more dyad "[saw] all three of these things [students, curriculum, and faculty] linked in ABET, […] the continuous improvement loop that ABET asks people to do."

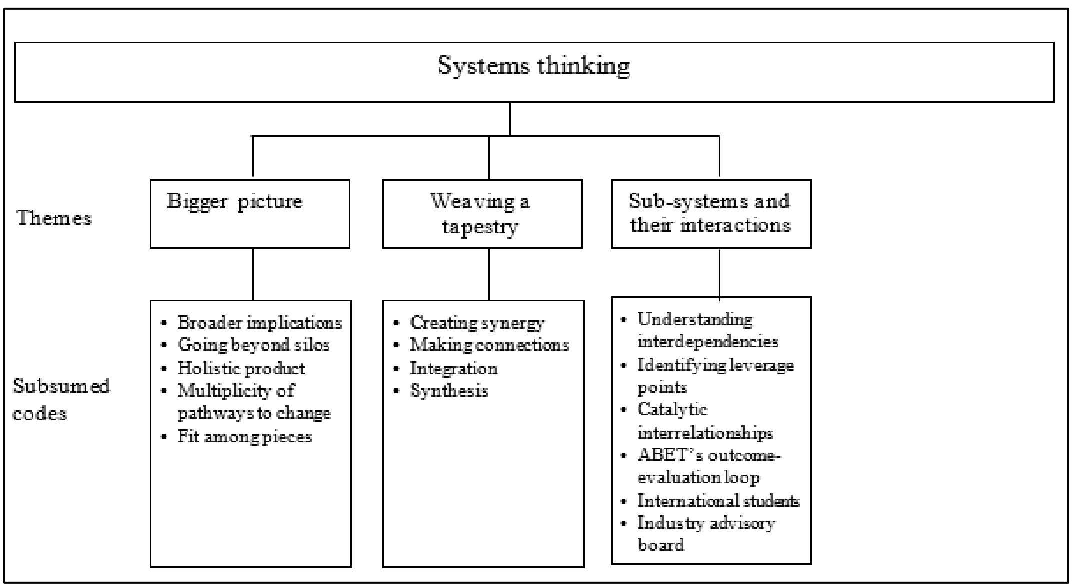

Figure 3.3. Coding tree for systems thinking. Format adapted from Borrego and Newswander, 2008.

Overall, systems thinking was focused in the local context of individual projects. Observations confirmed the lack of systems thinking in meeting discussions. Systems thinking was observed during just one out of six meetings, discussing an evaluation feedback loop to NSF.

Strategic thinking. Strategic thinking captured the focus of all teams' work covering numerous research activities ranging from conceptualization of research to evaluation and dissemination. An education researcher stated, "I think the one that really, really jumps out is that strategic thinking because it is the focus, a lot of it." The eight themes (Table 3.5) identified from interview data convey the attention to strategic thinking in the research process.

Developmental strategies described ideas that helped initiate and position projects in the "larger constellation of goals" or "fit within larger strategies" of the department or institute. References to "building on the strength" of the previous project or "identifying overlaps" with another grant for expansion were mentioned as part of project development strategies (Figure 3.4).

Strategic thinking was also conceptualized as developing a plan of action for the research. *Planning strategies* included general statements and specifics such as generational strategy, backward design, logic models. For example, one participant indicated, "So we put in a strategic plan together and we said, 'we are going to do this, this, this kind of activities."

Strategic thinking was also discussed from the implementation angle. One participant explained, "…strategic in terms of, we have limited resources, so how do we best use them, where do they have the biggest payoff, and how do we continue that growth trajectory?" For others, being strategic meant flexibility: "You've got to have some flexibility in your solutions. It's no absolute solution. It really relates to strategic thinking, where there's one best solution but there isn't a best solution." Some of the *implementation strategies* included "make it realistic," "benchmark and learn and talk to people," "use technology tools," and "figure out and share what exists, so we're not reinventing the wheel."

The cluster of *problem solving strategies* contained a number of codes that reflect the crux of strategic thinking which is different from strategic planning. The statements underneath described creative problem-solving approaches and alternatives. The notion of strategic problem solving was summed up by a participant as "using the scientific method in a different way, looking at creating different approaches to things that have been done before." One of the dyads suggested that this is what they are trying to teach their students: "the ability to think strategically the process of defining the problem or hypothesis, generating an experimental plan, executing that experiment and communicating the ideas with others."

A group of codes reflecting "some kind of measurement […] to know whether you've done it right or not," "capturing at the tail end," "looking at the outcomes," and "life-cycle analysis" were subsumed under *evaluation strategies*. The notion of evaluation as a strategy was driven by two elements: the NSF requirements and the desire to disseminate best practices.

Consensus building strategies described strategic thinking to generate buy-in from various stakeholders. The theme subsumed participants' thinking about resistant stakeholders or different classes of partners. Some of the strategies included "motivational interviewing," "motivational incentives," "conveying relevance across different fields," and "interactions to facilitate adoption." As one participant mentioned, strategic thinking meant "to create a coherent product that makes sense from these different perspectives of [engineering, psychology, education, and instructional design]."

Table 3.5

Participants' Conceptualizations of Strategic Thinking

Theme	Description	Example
Developmental strategies	Providing examples of strategic approaches to conceptualize or position projects	"They had an initiative for faculty that were willing to try to put together reflective education into their engineering classes. And it seemed to fit very nicely with some stuff that I was already doing."
Planning strategies	Developing a plan of action for the research projects	"We started with the end in mind and then we walked backward somewhat because we had these ideas of what we wanted but then you started looking at all the little pieces and is it strategic, is it possible? That is when we started making the tweaks and we were looking at, 'Well what are the outcomes of this and if we could do this' So, we did the backward design."
Implementation strategies	Using strategic courses of actions to execute the plan for research	"Which things can we do to a certain degree or this year? For example, we have to collect a lot more qualitative data and at first I personally kind of freaked out because I thought, well that's going to cost more money. But then of course one of the leaders said, 'well, wait a minute, what about if this year we start with one group?'"
Problem solving strategies	Using creative, out of the box strategies for problem-solving	"I think that there is an interesting aspect of synthesis through the application of some of these ideas in the context of engineering and where it is abductive reasoning and it is creative problem solving. It is also that you don't arrive at a right answer…it is about developing judgment and making trade-offs"
Evaluation strategies	Developing strategies to capture impact	"It is a systematic way of gathering what evidence we already have. Then looking at the outcomes and whatever data we collect then informs the next batch of interventions […] and how do we continue that growth trajectory.
Consensus building strategies	Strategically communicating with various audiences to negotiate a buy-in	"There are some times that I have to convince my engineering pals of what we need to do here is very important because of this and that and that. Not just because it is a mandatory thing and that is the point."
Collaboration strategies	Considering strategies that work and sustain the collaborative research	"I have always found that is really comfortable when you talk with the engineers, if you say design, develop and test. They do that anyway. Those concepts are really easy for engineers to understand. So when we do that with curriculum materials for example, makes sense."
Personal growth strategies	Thinking about strategies for personal and professional growth	"How do you know whether you have done it right or not? Obvious natural sequence to […] is some kind of an experiment in your class to see what the effects of doing this were. And then if you are doing that anyway, why not write it up as a research paper and publish in the engineering education research?"

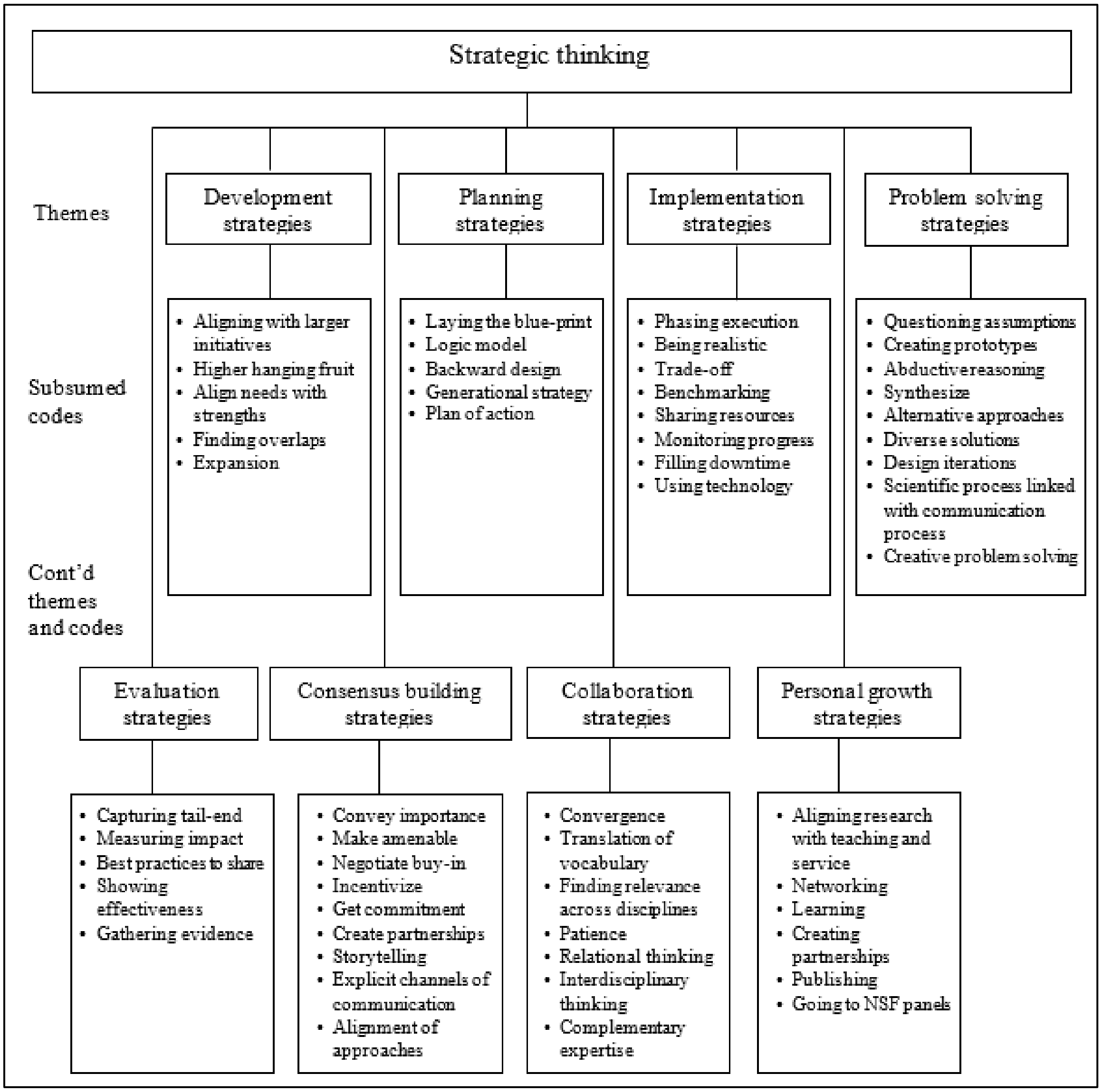

Figure 3.4. Coding tree for strategic thinking. Format adapted from Borrego and Newswander, 2008.

Seeking non-overlapping yet complementary expertise to create a partnership, interdisciplinary approaches, and relational thinking were part of *collaboration strategies* as evidenced by the following statement: "It's also important, when we talk about strategic thinking, that we're very good at bringing people from different backgrounds together, different academic disciplines. That also helps us in terms of design and outcomes and planning." For ERC participants, the idea of collaboration extended to industry "for greater societal impact and for the ability to take things to market more quickly."

Participants also conceptualized *personal growth strategies* as part of strategic thinking as they talked about networking, publishing, learning from their collaborators, and aligning the three elements (research, teaching, and service) of academic work. As one participant explained, "I am learning that how you teach it is probably about as important as what you are teaching. [Now] I say, 'What do you think? What are some possibilities' instead of, 'What is this about?'"

Strategic thinking was the most evident way of thinking during observations as strategies of allocating limited resources of time and funds. Discussions were had as well about innovative approaches to increase participation in research and evaluations of alternatives. Overall, strategic thinking translated into feasible actions on futures, values, and systems thinking.

Ways of Thinking: Applications and Implementation

With an understanding of how futures, values, systems, and strategic thinking are conceptualized for EER, the following subsection describes the application and implementation of these ways of thinking by participants in their research projects. Data are presented through embedded participant quotations included in a narrative description for each way of thinking in order to answer the second research question:

How are futures, values, systems, and strategic thinking implemented by collaborating engineering and social sciences researchers in their engineering education projects?

Futures thinking. Futures thinking was primarily applied by participants in grant writing "to write proposals that were transportable and sustainable" in the future.

Successful proposals usually “represented a model that could be applied in many different settings and could be used by other institutions.” Futures thinking was used by one dyad in the “participatory design arm [of the project] that was about imagining a future and using that to inform current designs and bringing users into that process.” Another dyad used futures thinking to design the ERC’s summer research experience program for undergraduates thinking of “students as the product. And then thinking about okay, I sound like an engineer. It's terrible, all of the features that this product needs to have” in the future.

Observations indicated that futures thinking was also utilized for publications planning that consequently informed decision-making regarding evaluation procedures for how much and how to collect data. Futures thinking involved learning from the past as participants discussed future plans based on previous year’s experiences and/or evaluation data. One computer engineer also mentioned incorporating futures thinking in her classes as a result of her engineering education research collaboration. She said, “I don't think, without this collaboration, I would be incorporating so much futures thinking or future-focused activities into my classes. So I do ... With every class, there are some activities where I ask them to imagine a future and think about a prototype 50 years into the future.”

Values thinking. Only one of the nine projects applied values thinking in their research design considering the values of equity, access, and inclusion. They modified an existing simulation system that was previously “designed by A+ students for other A+ students” to “make a system that worked for others, taking into account human factors and things like that to remove implicit biases.” Other participants talked about using values thinking to select a diverse cohort of summer participants, to provide gender-neutral examples while teaching, and developing a user-centered design "taking the user's culture into account."

Some values thinking was observed in team meetings with regard to Institutional Review Board procedures and arrangements of a diversity and inclusion webinar for ERC participants. Given the broad range of conceptualizations of values thinking described earlier, values thinking played a role in "put[ing] together a project where each of the discipline's values [were] represented" so it "[felt] like they were contributing but also getting something back out of it; and not contributing just for the sake of the other person's efforts."

Systems thinking. Most participants applied systems thinking in their local project context as evident from this statement, "One of the ways we thought we used systems thinking was to think about the linkages between the projects that we were defining, both in terms of the different labs that we represented and how it would affect those labs in our larger Center community." There were many examples of "synthesizing different parts of the project," "think[ing] about the linkages between the projects" or "make[ing] connections across various activities [of the project.]" One dyad provided an example of their grant-writing process as systems thinking: "linking different parts of the proposal together. What's being done, what isn't being done … what our measurable objectives are, what our evaluation scheme is going to be. So all of these things tied together as a system." One dyad admitted they failed to use systems thinking, "… where we really faltered was in systems thinking, because we never quite brought everything, all the different elements of the project together." They mentioned regrettably that otherwise "the three arms of the project" could have "learn[ed] from each other's findings for further research and development."

Strategic thinking. Strategic thinking was applied during typical grant and paper writing processes of planning, strategizing, coordinating, and responding to reviewer comments. One researcher explained, "A section in the grant proposal which talks about after this funding runs out, what are the next things that we are going to do […] that's where a lot of I think the strategic thinking comes in." Observations suggested that strategic thinking was used to "assess the relative merit of an approach" under consideration to steer the direction of the project. Strategic thinking was also used to discern logistics and to leverage the resources of time, talent, and budget effectively. As an example, one dyad mentioned that they "could have used further strategic thinking to build in the natural outflow and inflow of students graduating and joining" [the project] and to consider "explicit channels of actionable communication throughout the whole project."

Ways of Thinking: Challenges

Participants also identified challenges of implementation, while describing futures, values, systems, and strategic thinking in the context of EER. The following subsection describes rich, contextual data related to challenges to answer the third research question*:*

What are the challenges for collaborating engineering and social sciences researchers in implementing futures, values, systems, and strategic thinking?

In participants' descriptions of challenges associated with futures, values, systems, and strategic thinking, the leading theme was culture.

Culture. Culture was a recurring theme in conversations regarding challenges. For participants, culture reflected values as well as practices and emerging ideas. Values were seen as "the outward reflection of the culture," "the culture of the departments, the culture of the field," and "the culture of various groups and the society we live in."

A few participants indicated that the departmental cultures often send a message that seems antithetical to the core values of EER. An engineer stated, "I even heard somebody from the Provost's office once say that you are not going to make tenure on teaching, if it is really bad you could lose it. But that was all he really had to say about teaching." Another engineer questioned the practices, "I will teach versus I will profess and it is an antiquated distinction but I think it reflects on like what the expectations are of the educational systems that we are embedded in."

There were multiple references to the culture of the engineering field that values "formulaic approach(es)," "unbridled capitalism," and "dollar values." One engineer explained, "Academics, and I would say engineers in particular are, in my opinion, guilty more than anything else of working on the wrong problems" because they define "value of benefits per cost and competition and determine which problems to work on." Another researcher echoed the thought:

> I think that we also frequently convey, sometimes directly, maybe indirectly, to our students that if you can develop something that is bigger, better, faster, and that generates fervor and interest but also revenue, it is a good thing. My personal bent is that we do in fact need to encourage those things, but as well, we would want members of our center to understand the value of societal impact, […] the value of the life cycle sustainability assessment. Recognizing it is not just better, bigger, faster.

Cultural values were also questioned in terms of sustainable futures, environmental justice, and social justice as "You cannot put a dollar cost, necessarily, on a social impact." One researcher elaborated:

> We need to look at the social impacts too about how what we're doing affects the social fabric. Getting to the level of diversity in terms of, I think, races and gender and sustainability and environmental justice, we haven't quite integrated that into our thinking or our classroom, […] so which neighborhoods are benefiting and which are being left out. Those discussions, I think, are a way to begin to incorporate them, and ultimately I would like to see that as part of the pedagogy that is part of the classroom fabric. I don't think we are there yet […] it hasn't been codified in terms of how we embed that into the education, the training, and therefore the design thinking of engineers. [We need to change the culture so that] both students and faculty and staff feel a bit more comfortable in saying, 'Let us discuss these elements that are critical to the fabric, but aren't necessarily about the technical aspect.'

Overall, culture was seen as the "overarching umbrella" that affected all four ways of thinking as one participant described:

> You create a culture, and the culture will vary on whether it considers future generations, seven generations down the line, or whether it is focused on the immediacy of the situation. Culture creates practices that make you think about how things are interrelated, or it teaches you to only think about yourself and what is directly relevant to you. Whatever culture you are embedded in either promotes strategic thinking and being systematic, or it does not. The values that he mentioned, also derive from the culture.

Subsections below present "thick descriptions" (Geertz, 1973) to provide rich, contextual understanding of the challenges for each way of thinking and how culture plays a role.

Futures thinking. A few participants indicated that futures thinking was "hard to conceive" and others contributed the difficulty to a monolithic education system as evidenced by the statement, "Once you have a curriculum, it's hard to change a curriculum. Usually, it's like, 'We're going to take this out and we're going to put this in' as opposed to minimizing and customizing things." Many dyads ended up describing a near-term future because the immediate thoughts in their mind, partly due to the nature of work, were always focused either on NSF's evaluation requirements or on funding. An engineering researcher explained the challenges with futures thinking:

Some projects are very successful when funds are available, but the innovations developed and put in place will wither and fade after the funding is exhausted. Maybe in the immediate future I think is, how are we going to keep this stuff going next year or the year after when the funding is over. […] I think rather than futures thinking, because it's hard unless you're a soothsayer to look at the future, but what we think about really is the future in terms of continuous improvement. It's more short-term futures thinking based upon knowledge that you've acquired, which allows you to move forward.

All dyads discussed futures thinking primarily describing a near-term future that considers outcomes and impacts of their research. For example, the ERC program is set up to look ahead to help humanity and life with engineering solutions that address tomorrow's problems. The long-term thinking regarding future generations was absent in discussions with most of the ERC participants. Strategic thinking was of greater focus for their projects, rather than futures. At the end of an interview, an education researcher admitted:

So the whole thing is future oriented. But what's funny is the reason when you asked both [of us] that we immediately start thinking of, well what do we do? We do strategies, you know, and we make this stuff happen. But actually the whole purpose of the center is futures thinking. Oh my gosh, interesting how we missed that!

Values thinking. Values thinking was identified as the most difficult to implement due to challenges related to implicit biases, assumptions, tenure process, and embedded engineering culture. The challenges explained by participants coincided with varied interpretations of values thinking described earlier. An education researcher who has worked on four engineering education projects over a period of 13 years, explained the challenge:

It is difficult to get [values thinking] to be a main thrust. We have worked around the edges of this. We had to compromise because when you have all these people in the room and they are participating in a grant and you are not telling them this but what they are hearing is, everything they have ever done is wrong, that is what they are hearing.

She further added:

> The sticking point [is] some segment of the engineering culture and as it values ethical thinking, underrepresentation, understanding whether it fits culture. You just cannot come in with big feet and say, 'Okay, here is a new water pump.' If it doesn't fit with how people think of getting water, that pump is not going to work. That has been a little tough.

The one size fits all approach, often taken in design, was perceived as a cultural norm in engineering that hindered adoption of values thinking. While one engineering researcher suggested the need to "create an awareness and a realization that when you engineer solutions, you are not dealing with a homogenous set of users." Another engineer indicated that the process of "defining and finding value and hence determining which problems to work on in engineering" needs to change. He explained:

> Whether you are an engineer or educator, it turns out the circle of interesting problems is huge and you have to have some way of figuring out which ones you want to work on. It is better if you can find the subset within the interesting problems of the important problems. The ones that not only tickle your brain, but if you do something that matters. […] We assume that everybody acts rationally and that if it makes sense in our brain then it is valuable. [We need to take] research out of the lab to the problem definition space […] we need to pick up the phone and start talking to people. It is a hypothesis generation and testing that is probably much more familiar with social scientists and education researchers than it is to engineers.

Mismatch of values with colleagues or supervisors was another challenge as demonstrated by this statement by an engineer who wanted to pursue engineering education research over engineering research:

> When I work with folks, and a great example truthfully is the folks that are in the administration above me…We have such a mismatch in why we are doing this, what we are trying to accomplish that sometimes it is even difficult to speak to them, because it is almost like we're speaking different languages.

One of the observations confirmed this challenge as participants discussed not being able to attach a dollar value to professional development on active learning to convey its importance to the administrators. The challenge regarding convergence of values was further elaborated when an education researcher working at an ERC described the challenge of selecting a diverse cohort for their summer undergraduate research experience program:

> We struggled to think about what diversity means […] In our materials we were explicit about recruiting people from backgrounds that are traditionally been marginalized in Engineering, but then when we actually go to get sit down with the applications and think about diversity, we find that we have different ways of thinking about diversity and its importance, what it means and what we are trying to do with it. So, that was a conversation that had to get wrestled down.

Systems thinking. Despite being recognized as a crucial concept by all dyads, systems thinking was the least utilized way of thinking considering the larger ecosystem. As mentioned earlier, one dyad admitted failure to apply systems thinking in "connecting findings from three different elements of the projects to inform future work." They explained that logistics of time prevented the overarching systems level synthesis: "…we needed time to synthesize, reflect and find intersections and crossovers. But the intentionality was missing from the beginning [in the design or planning]. You are lucky if the intersections emerge from your project findings. [Because most of the times] systems thinking needs to be intentional."

Challenges of silos and system dynamics also seemed to hinder broader systems thinking. For example, one dyad indicated that though they were engaged in collaborative work across departmental boundaries, they "still worked in silos because, it's really easy as an educator to get ... after 38 years to see things a certain way because it's how it has been." The myopia as individuals continue to work within pre-set boundaries and the culture that goes along with it was explained by an engineer as, "I'm talking about whether our students can go get jobs in industry. And they're hearing jobs in industry, that's like a check mark, more donations from our, you know, students."

Systems dynamics also made implementation of systems thinking difficult for a few participants. An educator described the challenge as follows: "[Systems thinking] is a tough one. There are so many moving parts in education [and] education is the one thing where everybody is an expert because everybody has been in the system." One engineer described how program level changes made it difficult to work on their proposal which integrated design thinking across science, mathematics, and engineering:

> We put in a proposal, we did not get funded, we got some feedback and then we got together to revise the proposal and by the time we revised, we are in the middle of revision there is other changes going on within the [college] and so it was a funny thing to [walk out of a meeting] and one of the other people on our team going, 'Oh, I don't know that we should do this, I don't know that we should put in this proposal. It sounds like antithetical' […] so there is also some bit of that that is maybe systems thinking of like, if the person who is normally in charge of this academic unit is thinking creatively outside the box then that gives some support to us thinking laterally.

Strategic thinking. While none of the dyads explicitly identified challenges associated with strategic thinking, one dyad mentioned that despite having a strategic plan, sometimes they fell into a trap of reactive thinking:

> NSF evaluate us every year. And every year they tell us, 'why you are not doing this? Why you are not doing that?' So it is an extra element that probably they are putting in something that we did not plan for. In this moment, you can either, okay we demonstrate to NSF that we can do that in short, always short amount of times. And then we can fall into reactive mode in trying to check mark the requirements.

Discussion

The previous sections presented an authentic view of engineering education researcher's ways of thinking regarding problem-solving through the combination of conceptual themes, examples of resulting implementations, and contextual accounts of challenges. The investigation particularly focused on futures, values, systems, and strategic thinking adapted from the ESER. This section discusses the results and their implications by connecting them with literature in engineering education.

In spite of the limited experimental scope, the results of the current study affirm the pertinence and applicability of futures, values, systems, and strategic thinking for EER. Findings on futures thinking highlight the need for transferrable and sustainable research. Involvement of stakeholders (administrators, practitioners, departmental advisory boards) could be one of the means to achieve wider adoption of research outcomes and sustain practices beyond funding.

The theme of *incremental improvement*, implementation examples, and the challenges described by participants suggest focus on what will happen next as opposed to what could happen. A few participants referenced the needed transformation without the specifics on how to get there. This may suggest unpreparedness for possible futures in the next 10 to 20 years. Previous research and reports (Lande & Leifer, 2010; McKenna, Froyd, & Litzinger, 2014) have alluded to "recurring pattern of abundant short-term thinking" in the field (NAS, 2007, p. 25). Addressing the possibilities and probabilities of the future requires going beyond short-term considerations. Findings on futures thinking highlight the need for creative thinking to imagine what might look different in engineering education and using that imagination to inform current designs and processes (Alper, 2016; NAE, 2004).

Results also emphasize the need for values thinking in order to bring in a deliberate change in the professional practices. Values thinking, while acknowledged as relevant, diverged in meaning and adoption over a broad spectrum. Prior research has also hinted at the need to define the values of the field (Haghighi, 2005; Heywood, 2014; Jesiek, Newswander, & Borrego, 2009). The category of ethics was conspicuous by its absence. In spite of the reference to ethics in the definition of values thinking that was shown to the participants, direct references to engineering ethics (Barry & Herkert, 2014) or professional ethics were minimal and could only be inferred from the mentions of environmental or social justice by one particular dyad. One reason for the absence could be the nature of their projects. There is also a potential implication for researchers to engage in critical theory research that challenges traditional epistemic assumptions and illuminates the importance of social justice within engineering education.

The challenges associated with values thinking also imply the need to create further awareness about diversity and inclusion. Diversity of representation and voices in EER cannot be assumed (McKenna et al., 2018; Riley, Slaton, & Pawley, 2014). Research that engages audiences in different ways of thinking about diversity is urgently needed. This includes the diversity of class, nationality, queerness, disability, age – what it means, why it is important, and what the stakeholders can do to improve the current status within EER.

Regarding systems thinking, McKenna et al. (2014) wrote, “As a community we are collectively thinking more at the local level than the system level” (p. 189). Results confirm weakness in engaging with broader systems thinking despite talking about impact of the research with respect to futures thinking. Participants failed to make connections for their projects when asked to provide examples of systems thinking in the larger context of the engineering ecosystem. Systems thinking enables researchers to conceive problems from all angles of events, patterns, and structures to see the underlying “iceberg” (Kim, 1999). There is an implication here for a deeper inquiry examining the systems thinking of researchers or barriers that hinder expansive views of the engineering ecosystem.

Findings on strategic thinking signified diversity of solutions, flexibility, and opportunistic thinking throughout the research process. Strategic thinking, as indicated by all participants, plays a crucial role in the success of any research endeavor. Futures, values, and systems thinking are not a panacea until put in action through strategic thinking (Wiek et al., 2011a). This was evident as participants described seeking non-overlapping, yet complementary expertise to collaborate; which lays a blueprint to act upon decisions driven by futures, values and systems thinking.

Cultures and sub-cultures of programs, departments, institutes, and professional societies define values and create practices. The culture could be a boon or a barrier, and it can create silos or encourage interdisciplinary research and cross-pollination of ideas (Boden & Borrego, 2011). As the findings indicate, ways of thinking perpetuate and reinforce within cultures. One could argue that ways of thinking also influence culture (Schön, 1992). Future research could explore the intertwined relationship between ways of thinking and culture, looking at what specific practices or cultures can promote productive ways of thinking.

Ways of thinking as an approach that generates creative solutions to complex problems of practice could be a valuable tool particularly in EER endeavors. Within the actual practices of research and teaching, ways of thinking may be taken for granted or partly ignored despite their influence on innovation (Johansson-Sköldberg, Woodilla, & Çetinkaya, 2013). This study brings the appreciation for ways of thinking to the forefront which has a potential to push toward deep, systemic changes that can truly impact engineering education. Futures, values, systems, and strategic thinking are not heuristics, but they provide a structure for a solution-oriented outlook. They enable researchers to develop an expansive view of the problem at hand and build capacity to come up with solutions considering the cultures and long-term future. The different ways of thinking do not stand in competition with each other but could be developed and utilized in parallel. Together, futures, values, systems, and strategic thinking represent four main elements of a researcher's toolkit, necessary to critically engage with the broader ecosystem and challenge the status quo. They could encompass all conscious activities to challenge perceptions, design interventions, develop models, innovate processes, and garner deeper understanding of the underlying cultures to help us move toward better solutions and impactful approaches to complex problems.

Future Research

The current study represents the beginning of a scholarly exploration on ways of thinking for EER. The ultimate goal is a ways of thinking framework that articulates concrete abilities for specific ways of thinking pertinent to EER. To that end, future research could explore additional ways of thinking that might be relevant to EER endeavors (e.g., design thinking, entrepreneurial thinking, computational thinking), particularly within a global context. A survey was designed based on the results of this study to further explore the underlying dimensions of futures, values, systems, and strategic thinking. It was implemented nationwide targeting specific NSF awardees involved in interdisciplinary EER.

Future plans also include extending the inquiry to a larger number of engineering education projects at other institutes. Each individual way of thinking also provides a potential research track for a deeper inquiry using an ethnographic research design. The framework is perceived as particularly applicable for ERC participants because the ERC structure is futures oriented, has embedded education and diversity components, and uses systems thinking to address socio-technical issues. Other participating dyads also indicated that a ways of thinking framework could be valuable because it represents "things that we should be striving to achieve […], it goes to improving process, providing more structure." Future efforts could explore the application of the framework targeting ERC faculty and graduate students.

Conclusion

Engineering education is facing the persistent challenge of preparing 21^{st} century engineers capable of tackling the complex, global, and sociotechnical issues. This requires interdisciplinary research that is informed by novel ways of thinking. Combining futures, values, systems, and strategic thinking can help researchers to conceptualize and address a particular situation through a problem/solution pattern that may exist at a variety of temporal and spatial scales in the engineering education system.

CHAPTER 4

WAYS OF THINKING: A QUANTITATIVE INQUIRY

This chapter presents the final phase of a project designed to explore ways of thinking among collaborating engineering and social sciences researchers. The qualitative findings from the previous chapter were used to develop an original survey instrument, which was distributed across the United States. The goal was to expand upon the qualitative findings to gather a broader understanding of the nature of ways of thinking used in collaborative EER. The chapter includes the final quantitative inquiry, written as a third study.

The study details the instrument development, survey distribution processes, and the exploratory factor analysis results. Self-report data was gathered from engineering and social sciences researchers (n =111) involved in collaborative engineering education projects. Results convey the number and nature of factors underlying the scales of futures, values, systems, and strategic thinking for EER.

Like the previous chapters, this chapter is also written as a collaborative manuscript for publication. As a result, readers may note the use of passive voice and first person in the writing. Abbreviations and citations are also redefined.

Introduction

A well-established body of literature shows the benefits of interdisciplinary collaborations between engineering and social sciences researchers for the improvement of education in engineering colleges (Carr et al., 2017; McKenna, Yalvac, & Light, 2009; Olds, Moskal, & Miller, 2005; Ornelas, 2015). Such collaborative research typically involves drawing on theories and research methods from learning sciences, instructional design, or educational psychology and applying them to the teaching, learning, and other related activities within engineering and engineering education. Some examples include creating more inclusive engineering course designs, faculty development regarding novel pedagogical approaches, understanding mental models of students, and integrating engineering topics into traditional science education at the K-12 level (Aurigemma, Chandrasekharan, Nersessian, & Newstetter, 2013; Carberry & Church, 2009; Dalal, Larson, Zapata, Savenye, Hamdan, & Kavazanjian, 2017; Lehman, Kim, & Haris, 2014; Krause et al., 2015). Collaborating researchers share their domain-specific knowledge and skills, engage in meaning-making, evaluate multiple perspectives, and work together to solve the problems (Borrego & Newswander, 2008; Ornelas, 2015).

The underlying notion behind such collaborations is to foster innovation in the engineering education system. Millions of dollars are invested each year by a variety of funding agencies to research ways of improving existing engineering pedagogy. The National Science Foundation (NSF), a major contributor, often mandates a partnership between engineering researchers and social scientists to bring novel ways of thinking about educational research in the engineering domain (NSF, 2017; Wankat, Felder, Smith, & Oreovicz, 2002). This quotation from Dr. Elliot Douglas, former program director of the NSF, sums up this underlying notion:

> ‘You don’t start from I want to do this activity,’ said Douglas. ‘You start from I want to make this cultural change. That’s a very different way of thinking…‘Let’s think about how to not just cross-fertilize but cross-collaborate and create these larger partnerships that can work more broadly and at a larger scale to impact the engineering education field. What we want is broad, radical change in engineering education.’

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(Olson, 2018, p.8)

Adopting new ways of thinking is seen as one necessary means to bring about change and inform the existing practices within the larger engineering ecosystem (ASEE, 2014; NAE, 2004; NSF, 2017). A necessary first step is to better understand what ways of thinking are currently used in engineering education research (EER). Numerous activities associated with EER collaborations are not well documented. These include problem solving approaches, ways of thinking, vision, values, and strategies to ensure a successful engineering education collaboration. There are many unanswered questions. How do collaborators approach problem solving for engineering education? Are they focused on local context and changes or are they looking at system-wide transformation? Do they share a common transformational vision and values for the future of engineering education? What strategies do they implement to achieve the vision? What ways of thinking guide their decision-making for a lasting impact and a system wide transformation?

The current study aimed to explore these actions by assessing the ways of thinking used by engineering and social sciences researchers who came together for collaborative research. The notion of ways of thinking encompasses approaches to problem-solving informed by the literature in sustainability education, educational psychology, learning sciences, and business. A qualitative inquiry was previously conducted (Dalal, Archambault, & Carberry, 2019) to adapt a ways of thinking framework (Warren, Archambault, & Foley, 2014) developed within the context of Environmental and Sustainability Education Research for EER. A survey was designed and deployed based on the emergent, identified themes from this qualitative inquiry (Dalal et al., 2019).

The following sections describe the ways of thinking framework, instrument development, survey distribution processes, and initial exploratory factor analysis. The end goal of this line of inquiry is to develop a ways of thinking model that captures concrete abilities and research actions for linking ways of thinking to the goals of EER. The preliminary ways of thinking model from this first iteration has the potential to establish a foundation for an important tool for researchers to conceptualize and address a particular situation through a problem/solution pattern that may exist at a variety of temporal and spatial scales in the engineering education system.

Ways of Thinking

The term *ways of thinking* is often associated with a systematic thought process (Sousa, 2016). A variety of disciplines have further defined ways of thinking within their contexts. Learning sciences define ways of thinking as an approach to solving complex problems through coherent patterns in reasoning (Harel & Sowder, 2005). In the business and finance world, ways of thinking is a set of rules combined with an intuition of pattern recognition that leads to judgements and decisions (Douglas, 2000). Sustainability education sees ways of thinking as a lens to consider and address complex environmental education challenges (Warren et al., 2014). This study uses a combination of these definitions and operationalizes *ways of thinking* as a systematic thought process that informs decision-making to address complex educational challenges. It is not a heuristic, but rather an approach used by collaborating researchers to think, act, and engage with their research.

Different ways of thinking facilitate different strategies and subsequent actions to innovate. Accordingly, Warren et al. (2014) proposed four ways of thinking (Figure 2.1) – futures, values, systems, and strategic thinking – within the Sustainability Education Framework for Teachers (SEFT). *Futures thinking* focuses on exploring the present with anticipatory approaches to understand and prepare for future changes, problems, and solutions. *Values thinking* concerns the integration of justice, equity, and ethics in designing a solution. *Systems thinking* considers holistic approaches to problem-solving as ways to understand and analyze the complexity of various elements and their interrelationships in the overall ecosystem. *Strategic thinking* involves the ability to collectively develop a plan, design potential interventions, and consider possible alternatives that could lead to innovation in addressing today's challenges (Warren et al., 2014).

These ways of thinking while originally conceived to tackle educational challenges related to sustainability literacy, also apply to EER endeavors when used as a tool to consider complex problem/solution patterns in the engineering education system.

They link seemingly disparate topics and build capacity for problem-solving and addressing complex challenges. The following sub-sections describe each way of thinking in further detail and explain how they apply to EER.

Futures Thinking

Futures thinking focuses on working to address tomorrow's problems today with anticipatory approaches to understand and prepare for future changes, problems, and solutions (Warren et al., 2014). It entails learning from past decisions, understanding the present scenario, anticipating possible consequences of today's actions (or non-actions), and changing the nature of decision-making in the present (Miller, 2003; Warren et al., 2014; Wiek, Withycombe, & Redman, 2011a). *The Engineer of 2020* report provides an example of evidence demonstrating the alignment between futures thinking and engineering education. It shows that futures thinking is about pro-actively envisioning the roles that engineers will play in the future and advancing the state of the art in engineering education to prepare the future workforce (NAE, 2004).

Discussing research activities, Alper (2016) conceptualized futures thinking as an effort to "think broadly, think big picture, and think way out of the box" when considering the changes that may occur in the field of engineering education in the next few decades (p. 4). Consequently, futures thinking is about imagining disruption of existing patterns, considering diverse interdisciplinary perspectives, re-scoping of problem spaces, and developing models, processes, and practices that influence the larger engineering education community (Alper, 2016; Borrego & Henderson, 2014; Lande & Leifer, 2010; NAE, 2005). In sum, futures thinking involves bringing about profound change in current research practices considering "what engineering students should learn in the university to prepare for the future and how this might differ from what is taught today" (NAE, 2004, p. xiii).

Values Thinking

Values thinking is about recognizing the concepts of ethics, equity, and social justice in the context of varying cultures in order to make decisions (Warren et al., 2014). It is about the recognition of how decisions are made, not which decisions are correct (Vesilind, 1991). For the multi-faceted system of engineering education, values thinking translates into diversity and inclusion, social-humanistic approaches of research, and ethical engineering practices (Barry & Herkert, 2014; Douglas, Koro-Ljungberg, & Borrego, 2010; Guston, 2013; Lichtenstein, Chen, Smith, & Maldonado, 2014; Riley, Slaton, & Pawley, 2014; Sarkikoski, 1988).

The engineering system has been criticized for several issues relating to a significant gender gap, lack of underrepresented minorities, and an overall chilly climate toward non-dominant groups (McKenna, Dalal, Anderson, & Ta, 2018; Riley et al., 2014). This makes values thinking for many researchers about: 1) mirroring the society in the engineering education system considering diversity (Lichtenstein et al., 2014; Swan, Paterson, & Bielefeldt, 2014); and 2) creating a culture of inclusion (Mills, Ayre, & Gill, 2011; Riley et al., 2014).

Values thinking also entails recognition of the social-humanistic side of the engineering education system which translates into: 1) engineering ways of thinking that consider possible engineered solutions that are not only fair to a variety of different people but also transparent, sustainable, and equitable. (Guston, 2013; Wiek, Withycombe, Redman, & Mills, 2011b); and 2) appreciating diverse ways of knowing and considering contextual and individual experiences in research methodologies (Douglas, Koro-Ljungberg, & Borrego, 2010; Riley et al., 2014). Values thinking thus entails curricular changes to integrate ethical ways of thinking with technical expertise, challenging the traditional epistemic assumptions, selecting diverse voices and representation in research, and examining institutional practices and cultures. (Barry & Herkert, 2014; Guston, 2013; Lumsdaine, & Lumsdaine, 1995; McKenna et al., 2018; Riley et al., 2014). In sum, values thinking is about challenging the status quo and bringing in deliberative change to a culture and constructing new directions.

Systems Thinking

Systems thinking involves considering holistic approaches to problem-solving that understand and analyze the complexity of various elements and their interrelationships in the overall ecosystem (Kellam, Maher, & Peters, 2008; Warren et al., 2014). Systems thinking does not equate to complete knowledge, rather systems thinking is about "assessing the degree of system complexity and analyzing system dynamics to make informed decisions that reduce the risk of negative outcomes" (Warren et al., p. 8). It is the understanding of structure, functions, and causal loops (Spector & Davidsen, 1997).

The system of engineering education has been grappling with multiple chronic issues of student retention, diversity and inclusion, overloaded curricula, and traditional lecture-based pedagogy (Carberry & Ohland, 2012; Goals Committee, 1968; NAE, 2004; Swan et al., 2014). Past research has suggested the need for systems thinking to solve these issues because systems thinking allows for a "30,000 feet" perspective, broadens the problem space, and expands the choices for solutions (Borrego & Henderson, 2014;

McKenna, Froyd, & Litzinger, 2014). More satisfying solutions to chronic problems can be realized when understanding the whole system goes beyond the institution, administrators, students, faculty and curricula, to include the sub-systems of accreditation boards, industry, federal agencies, professional bodies, primary and secondary education, and the global economy (Godfrey, Crick, & Huang, 2014, McKenna et al., 2014). Due to its non-linear nature, systems thinking can help bring about transformation in the system leveraging interdependencies between sub-systems and cascading effects (Warren et al., 2014). Thus, systems thinking entails an awareness of the larger context, an ability to make connections while also understanding constraints, and an acceptance that elements that might be invisible can still govern the system (Meadows, 2008; Senge & Sterman, 1992).

Strategic Thinking

Strategic thinking is the ability to create a plan of action to achieve the desired vision (Warren et al., 2014). It involves envisioning goals and objectives, collectively developing a plan, and considering appropriate courses of action and resource allocation that could lead to innovation in addressing today's challenges (Wiek et al., 2011b). The converging forces of globalization, technology, and economic restructuring make strategic thinking an essential skill for engineers and consequently has implications for engineering education (De Graaff & Ravesteijn, 2001; Liao, Chen, & Wu, 2006). Literature suggests that engineering education researchers need to develop interventions that promote strategic thinking among students (Davidovitch, Parush, & Shtub, 2006; De Graaff & Ravesteijn, 2001; Garcia-Perez & Ayres, 2012; NAE, 2004).

Strategic thinking is also about creating interdisciplinary partnerships, identifying the most important problems in the field, staying aware of the potential disruptive advances in the field, flexibility in approaches and solutions, assessing the relative merit of a solution, effective management of resources, communicating with various stakeholders, and considering ways to disseminate research beyond academic readership in the context of EER (Borrego & Newswander, 2008; Darji & Jani, 2009; Halpin & Huang, 1995; Jesiek, Borrego, & Beddoes, 2010; NAE, 2008; NRC, 2012; Wiek et al., 2011b). Overall, strategic thinking is about creative problem solving strategies that could help address the complex engineering education problems (Lumsdaine & Lumsdaine, 1994).

Futures, values, systems, and strategic thinking are interconnected and offer an organizing structure for collaborators to frame decisions regarding problems/solutions. These ways of thinking can be implemented in conjunction with one another or used individually depending on the problem or situation under consideration. When used in a networked fashion, they link topics that may seem disconnected and build capacity for problem solving with respect to complex engineering education challenges. To better understand what factors contribute to the knowledge, skills, and attitudes necessary for each way of thinking, this study assessed the ways of thinking used by engineering and social sciences researchers in collaborative EER.

Research Question and Hypothesis

This study looked to address the following research question:

RQ: What are the underlying dimensions of futures, values, systems, and strategic thinking associated with interdisciplinary engineering education research?

A qualitative inquiry was previously conducted (Dalal et al., 2019) to explore conceptualizations of futures, values, systems, and strategic thinking in the context of collaborative EER. The study reported the following major findings for each way of thinking: 1) futures thinking included two broad categories of educating the future workforce and research practices, 2) values thinking was interpreted in many different ways and resulted in seven themes relating to diversity & inclusion values, research values, and personal values toward research, teaching, and collaboration, 3) systems thinking focused on local project level systems contrasting the literature that emphasizes broader context of the engineering ecosystem, and 4) strategic thinking centered on two broad categories of research-related and personal strategies. These earlier findings (Dalal et al., 2019), in conjunction with the literature, resulted in the following hypotheses developed for this study.

1) Futures thinking items will load on two factors: educating future workforce and research practices;

2) Values thinking items will load on three factors: diversity and inclusion, research, and personal values;

3) Systems thinking items will load on two factors regarding the: local project contexts and the broader engineering ecosystem;

4) Strategic thinking items will load on two factors: research-related strategies and personal strategies.

Research Methods

Instrument Development

The survey instrument was developed through iterative construction and validation over a three-month period. An initial draft of the instrument was prepared from the qualitative themes identified in a prior study (Dalal et al., 2019) using a mixed methods instrument development joint display (Creswell, 2015). The joint display tables allow for writing of survey items aligned with qualitative findings and thus facilitate meaningful integration of qualitative and quantitative data (Fetters, Curry, & Creswell, 2013; Guetterman, Fetters, & Creswell, 2015). Table 4.1 shows an example of how the joint display was used to build survey items from the qualitative findings.

Table 4.1

A Joint Display Example Showing the Mapping of Qualitative Code to Survey Item

Qualitative theme	Qualitative evidence	Quantitative item
Imagining	"We have to look at what 10, 15, 20 years down the line, what is education going to look like?" "I remember thinking about how meta cognition was not for instance a part of engineers' training. So, then thinking about it might could become a part of, to just kind of imagining that."	How important are/were the following actions considering futures thinking in the context of your engineering education project? 1. Engaging in scenario-building activities to imagine what engineering education would look like in the future.

Further refinement followed the scale development procedures recommended by DeVellis (2003). Items were developed using participants' authentic language and phrasing, avoiding long sentences and double barreling (DeVellis, 2003). A five-point Likert scale ranging from "not at all important" to "extremely important" was used to measure the importance of various activities associated with different ways of thinking, specifically in the context of participants' EER projects. A "no opinion" option was not offered because forcing participants to express their opinion often improves measurement (Weisberg, 2005). A definition of the specific way of thinking was provided before the Likert-type question to provide clarity. Demographic information was also collected for each participant (Appendix B).

The survey was designed to take approximately 15 minutes to complete using the online survey tool Qualtrics. Content validity was established through expert reviews and think aloud pilot sessions (Dillman, Smyth, & Christian, 2014; Ericson & Simon, 1993; Fowler, 2002). Three experts (two engineering education researchers and one co-author of the SEFT framework) reviewed the instrument in its entirety. Edits were made on the initial draft based on their feedback. Next, think aloud pilot sessions were conducted with four faculty members, two each from the engineering and social sciences disciplines. One engineering and one social sciences faculty had participated in the previous qualitative study (Dalal et al., 2019). Changes made based on the think aloud sessions included simplifying the language of the systems thinking related items. For example, the item 'Uncovering elemental interactions of a given problem that may exist at different scales (local or global) of the system' was simplified to 'Uncovering interactions of elements within the engineering education system for a given problem.' Another item used the wording, 'Identifying cascading effects of a solution in one part of the system on other components.' Participants had difficulty understanding which part/component. This item was reworded as 'Identifying cascading effects of a given solution on other components within the engineering education system.'

Sample and Participants

The recruitment process involving non-probabilistic sampling was two-fold. First, the potential survey participants were selected from among awardees listed in the public database on the NSF website (https://www.nsf.gov/awardsearch). The database search was limited to two specific programs within the Division of Engineering Education and Centers that stated a required collaboration between an engineer and a social scientist. Second, listservs created within these programs were used to reach other researchers who participated in the projects but were not necessarily listed as a principal investigator (PI) or co-principal investigator (Co-PI) on the NSF site.

A total population of 310 researchers across 65 institutes resulted from these two processes. The 65 different U.S. institutions included 38 doctoral universities with very high research activity, 15 doctoral universities with high research activity, four doctoral/professional universities, five master's colleges and universities with larger programs, two baccalaureate colleges with art and science focus, and one special focus four-year technology-related school (The Carnegie classification, n.d.). A total of 293 researchers were contacted with 130 responses received. The received response rate of 44.4% is above the acceptable rate of 34% for web-based surveys (Shih & Fan, 2008). Figure 4.1 outlines the breakdown of final participant count from the potential sample and Table 4.2 displays the demographics for the final sample of 111 researchers. The average interdisciplinary research experience of participants was 8.7 years ranging from two to 37 years. Teaching experience ranged from one to 41 years, with an average of 16.5 years.

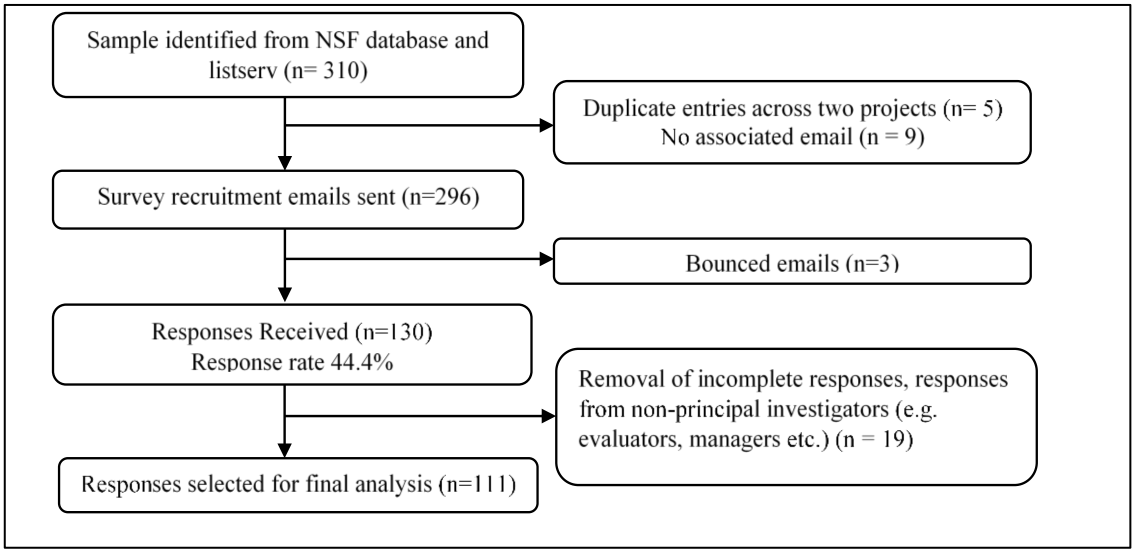

Figure 4.1. Breakdown of final participant count from the selected sample.

Table 4.2

Profile of Participants

Demographic	Response count	Response %
Rank		
Professor	32	28.8
Associate Professor	34	30.6
Assistant Professor	18	16.2
Research Professor	20	18.1
Unspecified	7	6.3
Discipline		
Engineering	28	25.2
Social sciences	20	18.0
Both including Engineering Education	47	42.4
Unspecified	16	14.4
Role on the project		
PI	36	32.4
Co-PI	55	49.5
Unspecified	20	18.1

Data Collection

In the fall of 2018, the survey was deployed over a five-week period in October using the Tailored Design Method (Dillman et al., 2014) of web-based surveys. A pre-notification was sent three days ahead of the survey link describing the survey and informed consent information. The pre-notification email allowed the research team to identify typographical errors in the email entries as well as inactive email accounts. Next, the survey link was emailed to the potential respondents. To increase the response rate, three reminders were sent once a week while the survey was open (Appendix C). Amazon e-gift cards were also raffled off as an incentive. Raffle entries were collected using a separate link to maintain participant response anonymity.

Data Analysis

Responses to the survey were analyzed using the Statistical Program for Social Sciences (SPSS) version 25. Descriptive statistics including mean and standard deviation were calculated for all items. Reliability analysis using Cronbach's alpha was conducted for each of the scales of futures, values, systems, and strategic thinking to ensure the internal consistency of the items (Cronbach, 1951). The correlation matrix was examined. Bartlett's sphericity and the Kaiser-Meyer-Olkin tests were conducted to ensure enough common variance among variables. After establishing the factorability of the dataset, an exploratory factor analysis (EFA) using Promax rotation was conducted to elicit evidence of the underlying factor structure for the items under each way of thinking (Brown, 2015). The number of factors extracted was determined using parallel analysis with principal axis factoring (Crawford et al., 2010) and scree plot tests.

Results

Determining Reliability and Factorability of the Dataset

Reliability of the items under each way of thinking was assessed using Cronbach's alpha with a criterion of 0.70 indicating good reliability (Cronbach, 1951). The Cronbach's alpha values were .869, .807, .910, and .885 for futures, values, systems, and strategic thinking respectively. Results of sphericity and sampling adequacy tests supported factorability of the dataset. Bartlett's sphericity test values were 401.157, 329.244, 458.726, and 462.985, $p < .001$ for futures, values, systems, and strategic thinking respectively. The Kaiser-Meyer-Olkin measures of sampling adequacy for futures, values, systems, and strategic thinking were .865, .757, .897 and .847 respectively.

Exploratory Factor Analysis

Four separate EFAs were conducted for each scale linked to each way of thinking construct. The following subsections present the results for each way of thinking.

Futures thinking. The means for each of the 10 items under futures thinking ranged from 2.56 to 4.18 (Table 4.3). The correlation values among all items ranged from 0.211 to 0.663 (Table 4.3). The scree plot and parallel analysis both suggested two underlying factors (Figure 4.2 and Figure 4.3). EFA confirmed the existence of two separate factors for futures thinking.

Table 4.3

Correlations, Means, and Standard Deviations for Futures Thinking Items

Measure	F1	F2	F3	F4	F5	F6	F7	F8	F9	*M*	*SD*
F1	1									2.56	1.37
F2	0.401	1								3.50	1.38
F3	0.279	0.478	1							3.77	1.14
F4	0.456	0.293	0.447	1						3.76	1.14
F5	0.488	0.566	0.393	0.453	1					3.07	1.49
F6	0.523	0.393	0.449	0.549	0.609	1				3.43	1.32
F7	0.422	0.253	0.250	0.326	0.462	0.550	1			3.40	1.09
F8	0.350	0.254	0.304	0.395	0.335	0.277	0.261	1		4.18	1.19
F9	0.463	0.318	0.342	0.390	0.451	0.446	0.385	0.663	1	3.71	1.30
F10	0.499	0.375	0.308	0.339	0.397	0.345	0.211	0.514	0.496	3.03	1.58

Note. *N* = 111. *M* = mean. *SD* = standard deviation. F1 through F10 refer to survey items for futures thinking.

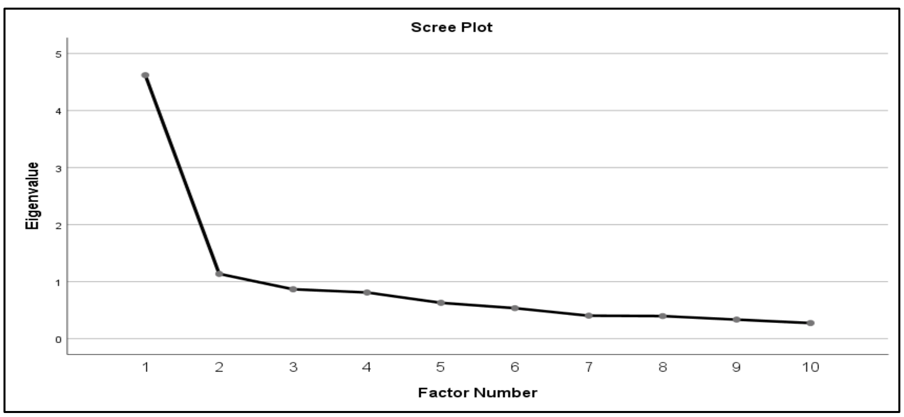

Figure 4.2. Scree plot for the measure of futures thinking.

All ten measures of futures thinking loaded independently on one of two factors with eigenvalues of 4.14 and 0.76 (Table 4.4). Factor loadings less than 0.400 were dismissed (Costello & Osborne, 2005). The two-factor solution accounted for 49.98% of the total variance divided into 41.35% (Factor 1) and 7.63% (Factor 2). The two factors correlated at 0.60 with no significance.

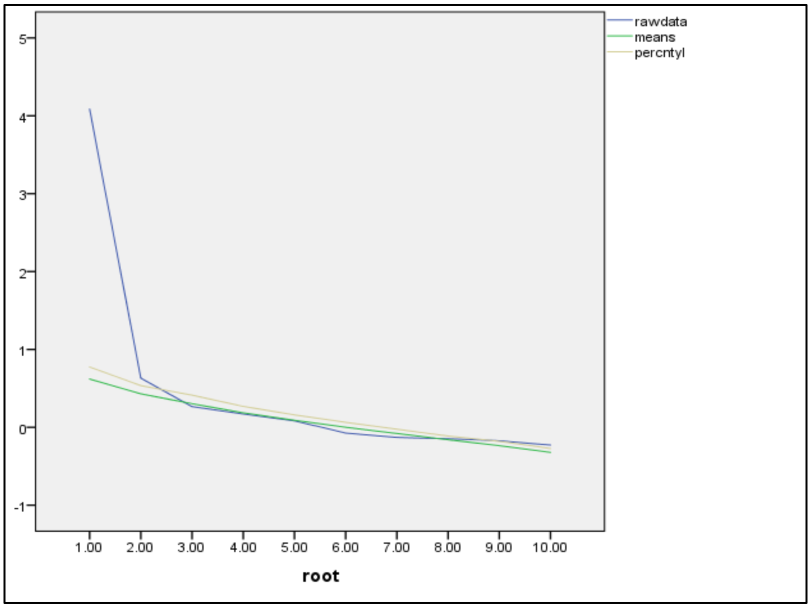

Figure 4.3. Parallel analysis plot for the measure of futures thinking.

Table 4.4

Factor Loadings for Futures Thinking

Measure	Factor 1	Factor 2
F1. Engaging in scenario-building activities to imagine what engineering education might look like in the future	0.548	
F2. Changing teaching practices of engineering faculty through professional development	0.508	
F3. Selecting research projects that have a potential for long lasting impact	0.449	
F4. Adopting research practices to drive transformational change (e.g., examining the past, understanding trends, identifying problems, and developing focused questions)	0.533	
F5. Encouraging administrators to provide necessary infrastructure to support grant projects after external funding has expired	0.779	
F6. Focusing on ways to improve the translation of research to practice	0.912	
F7. Engaging in short-term thinking to impact the immediate future (1-2 years)	0.596	
F8. Preparing students to become future professionals		0.954
F9. Preparing students to become contributing citizens of society		0.651
F10. Changing curricula to include course(s) not currently taught in the degree programs		0.520

Note. All values based on EFA with Promax Rotation (*N*=111).

Factor 1 included items related to research practices and outcomes looking ahead into the short-term and long-term future and was conceptualized as *research practices.* The items were focused around the notion of transforming engineering education through impactful and sustainable research. The measures included the broad concepts that have been identified as some of the means to transform engineering education, including bridging the research-to-practice gap, change mechanisms such as scenario-building, administrative support, and understanding implications and impact of research (Boden & Borrego, 2011; Borrego & Henderson, 2014; Finelli, Daly, & Richardson, 2014; London & Borrego, 2017). Overall, Factor 1 centered on repositioning engineering education with a futures-based approach of research that thinks about what could happen, as opposed to what will happen.

Factor 2 contained items that were focused on the teaching and learning practices and outcomes. The central notion behind the measures under Factor 2 was to prepare students as future citizens and professionals and hence the factor was conceptualized as *educating future workforce*. The emphasis was on engineering education rather than research, hence the item related to curricular changes (F10) loaded with the items focused on student preparation (F8 and F9). Overall, the two identified factors reflected EER and engineering education, which have been differentiated in the literature (Froyd & Lohmann, 2014).

Values thinking. The item means under values thinking ranged from 1.82 to 3.35 (Table 4.5). The zero-order correlation values among items spanned a wide range from a negligible value of 0.039 to a very high value of 0.845 (Mukaka, 2012). The scree plot suggested two underlying factors (Figure 4.4), while parallel analysis suggested three underlying factors (Figure 4.5). The three-factor model did not converge suggesting the use of a two-factor model.

Table 4.5

Correlations, Means, and Standard Deviations for Values Thinking Items

Measure	V1	V2	V3	V4	V5	V6	V7	V8	*M*	*SD*
V1	1								4.23	1.06
V2	0.845	1							4.19	1.15
V3	0.529	0.500	1						4.06	1.13
V4	0.374	0.317	0.349	1					3.35	1.18
V5	0.301	0.223	0.296	0.548	1				3.55	1.30
V6	0.479	0.393	0.405	0.391	0.495	1			3.49	1.28
V7	0.254	0.247	0.280	0.197	0.210	0.221	1		4.22	1.04
V8	0.368	0.317	0.346	0.309	0.201	0.215	0.166	1	3.78	1.17
V9	0.197	0.092	0.310	0.039	0.047	0.213	0.270	0.380	4.25	0.87

Note. *N* = 111. *M* = mean. *SD* = standard deviation. V1 through V9 refer to survey items for values thinking.

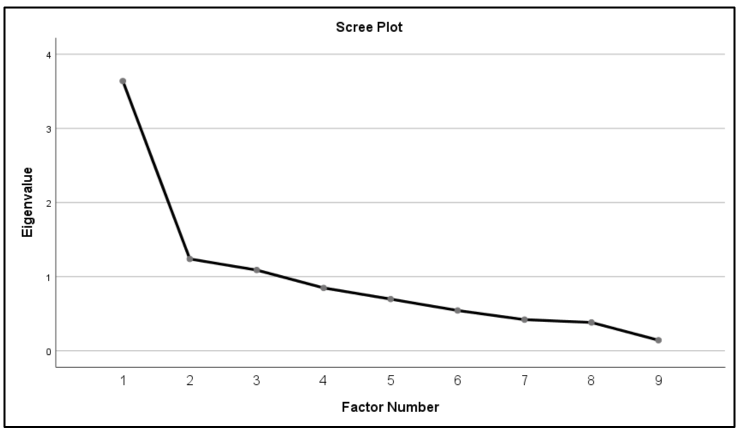

Figure 4.4. Scree plot for the measure of values thinking.

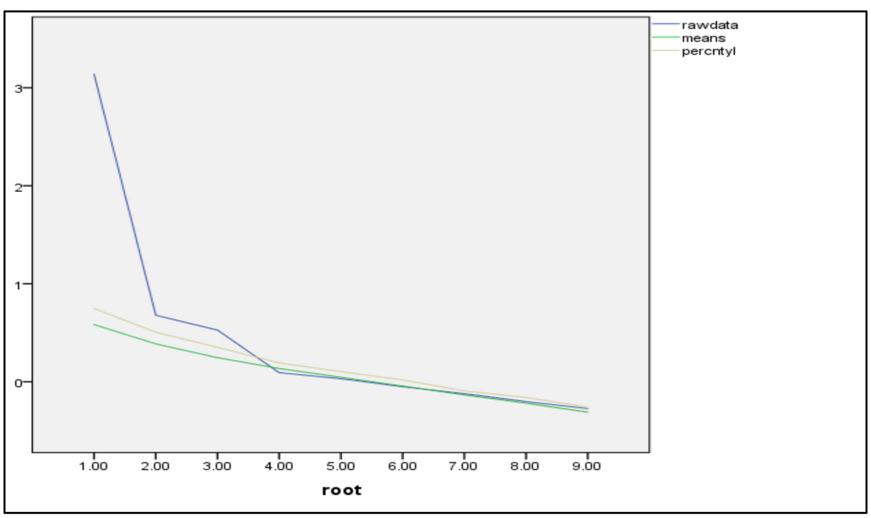

Figure 4.5. Parallel analysis plot for the measure of values thinking.

On the two-factor solution, only six items loaded independently on one of two factors (Table 4.6) with eigenvalues for the two-factors at 4.64 and 1.15. The two factor solution accounted for 44.39% of the total variance divided into 35.34% (Factor 1) and 9.05% (Factor 2). The two factors were correlated at 0.48 with no significance.

Table 4.6

Factor Loadings for Values Thinking

Measure	Factor 1	Factor 2
V1. Valuing diversity in the profession	0.931	
V2. Valuing inclusion in the profession	0.877	
V3. Considering the heterogeneity of the end user(s) when creating a solution (e.g., differences in users' gender, ethnicity, age, experience, etc.)	0.551	
V4. Reconciling personal values with those of your collaborator(s)		0.575
V5. Aligning personal values with the engineering education research		0.890
V6. Aligning societal values with the engineering education research		0.475
V7. Improving engineering teaching for addressing the needs of all students		
V8. Using research methodologies that highlight the value of context		
V9. Creating new knowledge through engineering education research		

Note. All values based on EFA with Promax Rotation (*N*=111).

Items V1, V2 and V3 loaded strongly on Factor 1 conceptualized as *diversity and inclusion.* The measures were about recognizing the concepts of diversity, inclusion, and heterogeneity among people. Factor 1 reflects the value of diverse viewpoints and the idea of building an engineering profession considering the demographics of the society (JEE, 2006; McKenna et al., 2018).

Factor 2 conceptualized as *personal values* reflects participants' thinking regarding personal, collaborative, and societal aspects of EER. Personal values and beliefs such as a desire to provide quality education, questioning one's own disciplinary thinking, openness toward other perspectives, and the drive for innovation often influence faculty members to pursue interdisciplinary, and collaborative EER (Allendoerfer, Adams, Bell, Fleming, & Leifer, 2007; Borrego & Newswander, 2008; Carson, 2015).

Personal values then combine with professional values to achieve a successful collaboration and make an impact in the society.

Systems thinking. The item means under systems thinking ranged from 2.97 to 3.80 (Table 4.7). The items were correlated in the moderate to high range (.30 to .70) but were not high enough to suggest a clear overlap and removal of items (Mukaka, 2012).

Table 4.7

Correlations, Means, and Standard Deviations for Systems Thinking Items

Measure	SY1	SY2	SY3	SY4	SY5	SY6	SY7	*M*	*SD*
SY1	1							3.34	1.27
SY2	0.516	1						3.62	1.17
SY3	0.500	0.413	1					3.80	1.14
SY4	0.499	0.520	0.571	1				3.13	1.38
SY5	0.632	0.476	0.505	0.677	1			3.04	1.33
SY6	0.424	0.519	0.372	0.590	0.530	1		3.71	1.20
SY7	0.440	0.567	0.464	0.668	0.546	0.689	1	3.26	1.38
SY8	0.622	0.596	0.450	0.706	0.665	0.583	0.685	2.97	1.40

Note. *N* = 111. *M* = mean. *SD* = standard deviation. SY1 through SY8 refer to survey items for systems thinking.

The Scree plot and parallel analysis both suggested one underlying factor (Figure 4.6, Figure 4.7). EFA confirmed one factor with eigenvalue of 4.46 which accounted for 55.73% of the total variance. Table 4.8 displays the factor loadings for all eight items.

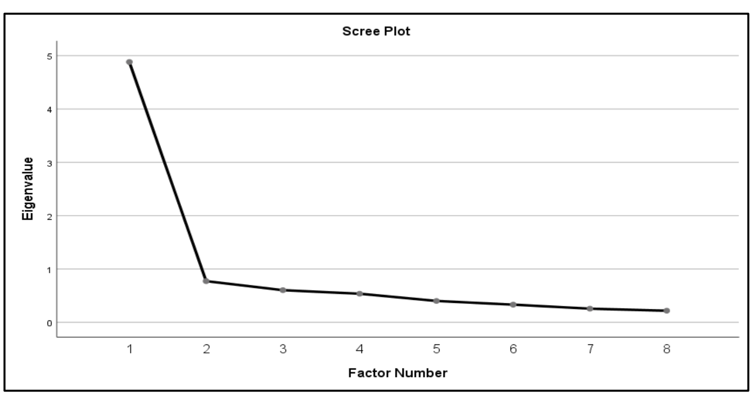

Figure 4.6. Scree plot for the measure of systems thinking.

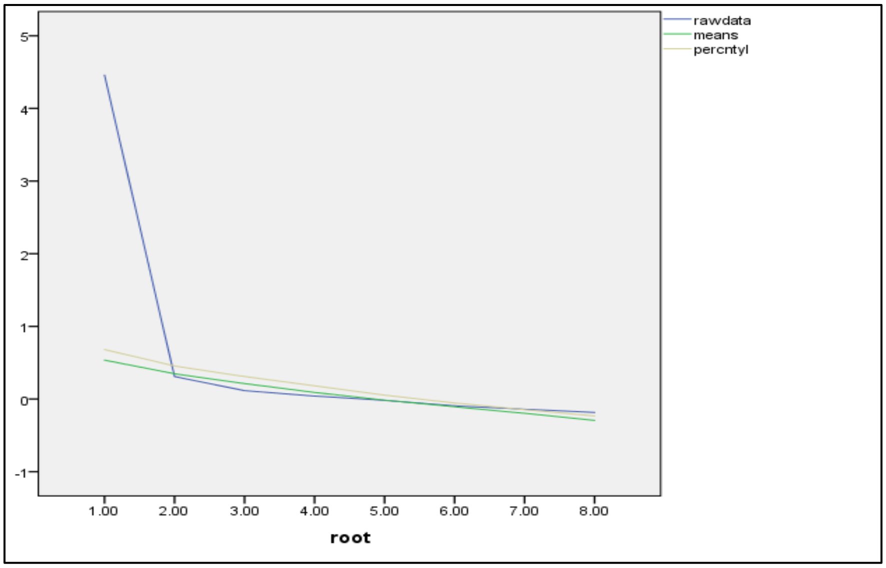

Figure 4.7. Parallel analysis plot for the measure of systems thinking.

Table 4.8

Factor Loadings for Systems Thinking

Measure	Factor 1
SY1. Recognizing that a given problem may exist at different scales (local or global)	0.688
SY2. Integrating different aspects of the project to ensure synergy across all components	0.685
SY3. Recognizing the implications of the project on all the stakeholders, even those not directly engaged as users, researchers, or collaborators	0.614
SY4. Recognizing the interdependence of components within the whole engineering education system (e.g., K-12 system, accreditation bodies, funding agencies, industry etc.)	0.827
SY5. Uncovering interactions of elements within the engineering education system	0.780
SY6. Thinking about implications of research in the larger context of the ecosystem	0.712
SY7. Identifying cascading effects of a given solution on other components within the engineering education system	0.788
SY8. Formulating problems considering the dynamic nature of the education system	0.848

Note. All values based on EFA with Promax Rotation (*N*=111).

The resulting one factor was conceptualized as *sub-systems and interdependencies*. It captured participants' understanding of intersections among various elements of a system. The items included references to the local systems of participants' research projects as well as the broader engineering education ecosystem. However, participants did not differentiate between the two. The one factor captures various concepts related to systems thinking that include, using a holistic approach, interactions with other systems, interactions of the parts of the system, cascading effects, and broader contexts (Kellam et al., 2008; McKenna et al., 2014; Spector & Davidsen, 1997).

Strategic thinking. The means for the nine items under strategic thinking ranged from 3.52 to 4.34, which suggested higher perceived importance of strategic thinking among participants. The correlation values among items ranged from 0.310 to 0.753 (Table 4.9).

Table 4.9

Correlations, Means, and Standard Deviations for Strategic Thinking Items

Measure	ST1	ST2	ST3	ST4	ST5	ST6	ST7	ST8	*M*	*SD*
ST1	1								3.52	1.26
ST2	0.631	1							3.90	1.04
ST3	0.350	0.558	1						4.34	0.85
ST4	0.467	0.601	0.683	1					4.13	1.00
ST5	0.493	0.488	0.412	0.566	1				3.79	1.12
ST6	0.411	0.434	0.450	0.581	0.362	1			3.85	1.18
ST7	0.494	0.548	0.501	0.651	0.524	0.630	1		3.94	0.99
ST8	0.352	0.310	0.376	0.395	0.358	0.411	0.525	1	3.70	1.17
ST9	0.381	0.444	0.454	0.408	0.443	0.473	0.545	0.753	3.60	1.19

Note. N = 111. *M* = mean. *SD* = standard deviation. ST1 through ST9 refer to survey items for strategic thinking.

The scree plot and parallel analysis both suggested two underlying factors (Figure 4.8, Figure 4.9). EFA confirmed the existence of two separate factors (Table 4.10). All nine measures of strategic thinking loaded independently upon one of the two factors with eigenvalues of 4.49 and 0.74. The two-factor solution accounted for 58.18% of the total variance divided into 49.94% (Factor 1) and 8.24 (Factor 2). The two factors correlated at 0.63 with no significance.

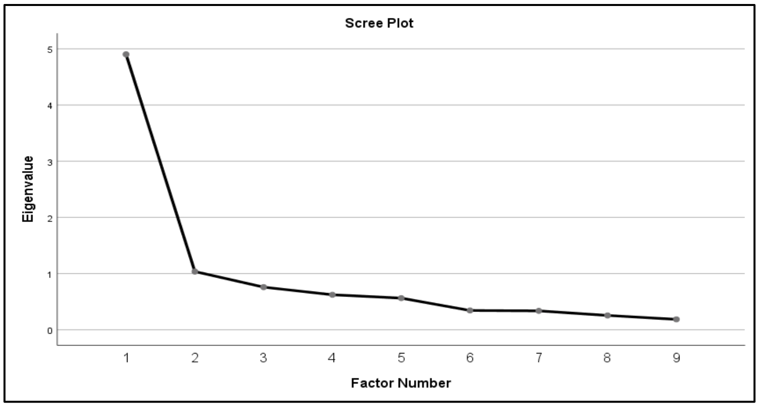

Figure 4.8. Scree plot for the measure of strategic thinking.

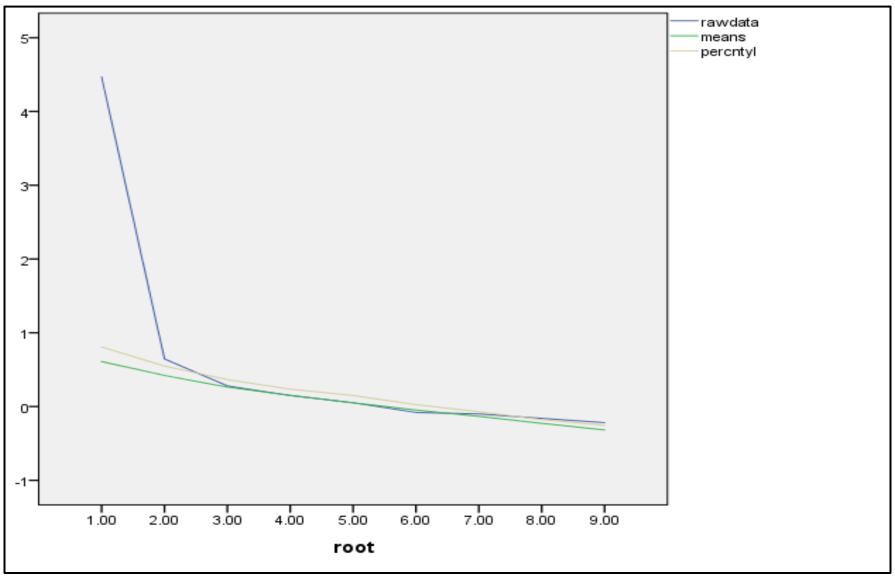

Figure 4.9. Parallel analysis plot for the measure of systems thinking.

Factor 1 conceptualized as *research related strategies* covered participants' strategic thinking regarding research activities. It contained items reflecting various strategies that could be used at different stages of research from conceptualization to planning, implementation, evaluation, and dissemination. These items and resulting factor confirmed the type of strategic thinking that goes in any EER endeavor beginning with positioning of the research project, identifying overlaps, building on prior research, planning the execution steps, managing the resources, and communicating with different stakeholders.

Factor 2, which was conceptualized as *personal strategies*, focused on the strategic thinking of participants regarding their collaboration as well as personal and professional growth. The two items that loaded on this factor align with the strategies researchers consider when looking for a collaborator, which may include shared goals, complementary expertise, clear expectations, compatible personalities, and career growth (Borrego & Newswander, 2008; Lattuca, 2001).

Table 4.10

Factor Loadings for Strategic Thinking

Measure	Factor 1	Factor 2
ST1. Developing strategies to position your research within larger initiatives of your or your collaborator's organization	0.637	
ST2. Employing strategies to convey importance of your research to various audiences	0.831	
ST3. Creating an overall plan for what is involved in the project	0.666	
ST4. Developing strategic courses of action to execute the project	0.905	
ST5. Using creative approaches to strategically address a challenging situation	0.605	
ST6. Using evaluation strategies to capture the impact of your research	0.532	
ST7. Improving strategies based on lessons learned	0.625	
ST8. Applying strategies that seek to strengthen your collaboration		0.914
ST9. Developing strategies that contribute to your professional growth (e.g., diversifying for broader learning, relationship building, etc.)		0.820

Note. All values based on EFA with Promax Rotation (*N*=111).

Discussion

This study is a first step toward quantitatively examining futures, values, systems, and strategic thinking in the context of interdisciplinary collaborations between and among engineering and social sciences researchers. Findings suggest the nature of researchers' ways of thinking and provide guidance for future iterations of the instrument. In the following section, we discuss the findings for each way of thinking and their implications connecting with literature.

Hypothesis 1. Futures thinking items will load on two factors: The two factor EFA-model aligned with the hypothesis and yielded interpretable results and fairly clean loading patterns. The two factors of *research practices* and *educating future workforce* align with the concepts of EER and engineering education, often differentiated in the literature (Haghighi, 2005; Jesiek, Newswander, & Borrego, 2009; Johri & Olds, 2014). While the term ‘engineering education’ is associated with the teaching and learning practices of engineering content, EER is considered a field of scientific inquiry about engineering education (Froyd, & Lohmann, 2014; Haghighi, 2005). The separate loading of items related to students and curricula suggest a distinction that researchers made between education practices and research.

We had expected the item (F2) related to teaching practices of faculty to also load on Factor 2 based on prior qualitative findings (Dalal et al., 2019). It is possible that participants associated the use of words ‘changing the practices’ in the item with research because: 1) research informs and changes existing teaching practices (Finelli et al., 2014**)** and 2) many researchers are involved in EER related to professional development of engineering faculty (Felder, Brent, & Prince, 2011; Krause et al, 2015). Follow-up iterations should shed light on this perplexing finding.

Hypothesis 2. Values thinking items will load on three factors: Findings for values thinking suggest a need for additional items, further specificity on the existing items, and more data to verify the existence of three factors. For example, item V8 (‘Using research methodologies that highlight the value of context’) could be revised to include the word ‘qualitative methodologies’ for specificity. The items were informed by the prior qualitative study (Dalal et al., 2019), which concluded that values thinking was a complex construct that varied in meaning and adoption, especially for EER. The instrument will need to be revised to better represent the values of the engineering education field. While the field has made progress toward defining goals and objectives (JEE 2006; Johri & Olds, 2014), the values that inform the practices of research and supporting infrastructures are still ambiguous (Heywood, 2014; Jesiek, et al., 2009).

It should be noted that while we expected the items on diversity and inclusion (V1 and V2) to load together, diversity and inclusion are two different concepts (Morely, 2018; Taylor, 2015). Researchers are just beginning to differentiate between the two. Future implementations of the instrument would still see these items loading on the same factor, but the correlation value should decrease as awareness of the differences between diversity and inclusion increases.

Hypothesis 3. Systems thinking items will load on two factors: Results on systems thinking did not match the hypothesis. Items were designed to differentiate between the local project context and the larger engineering education ecosystem. The items regarding the larger engineering education system were included based on the literature that recognizes the role of other peripheral elements (e.g., K-12 system, ABET, or funding agencies) in the overall ecosystem under broader systems thinking (Godfrey et al., 2014; Kellam et al., 2008; McKenna et al., 2014). However, participants did not differentiate between the local context and the broader ecosystem suggesting that items were not specific enough or that these systems considerations are not internally differentiated by the respondents. The identified one factor seems to capture the systems perspective from all levels. Items will need to be reworded especially, those pertaining to the local context (e.g., SY2, SY3) to explore whether these contexts can be differentiated and separated.

Hypothesis 4. Strategic thinking items will load on two factors: As hypothesized, strategic thinking was driven by two underlying factors of *research related strategies* as well as *personal strategies*. The two-factor EFA model on strategic thinking yielded clean loading patterns. The resulting two factor solution, in particular, the presence of personal growth and collaboration strategies, parallel prior literature that discusses strategies used by interdisciplinary collaborators to deal with epistemological differences between disciplines, skills of the team personnel, and the institutional policies in order to actualize success (Carson, 2015; Lattuca, 2001; Miller & Mansilla, 2004).

The objective for this study was to understand the underlying factors that influence researchers' ways of thinking, specifically in the context of collaborative research. Ways of thinking as an approach to address complex educational problems could be a valuable tool in EER endeavors. Ways of thinking are often taken for granted or ignored in actual practices despite their influence on innovation (Johansson-Sköldberg, Woodilla, & Çetinkaya, 2013). Futures, values, systems, and strategic thinking are not heuristics, but they have a potential to push toward deep, systemic changes that can truly impact engineering education. This study represents the beginning of a scholarly exploration on ways of thinking for EER. The ultimate goal is to create a model that captures underlying dimensions of futures, values, systems, and strategic thinking pertinent to EER. Such a model could provide a structure for solution-oriented outlook to meet EER goals.

Implications

This study, to our knowledge, is one of the first attempts to quantitatively examine ways of thinking constructs in the context of collaborative EER. We envision that the instrument developed from this study and future refinements can have multiple practical uses. First, researchers can use items under each way of thinking to inform their research related to futures, values, systems, or strategic thinking. Second, from our review of the literature and prior qualitative inquiry (Dalal et al., 2019) we compiled a list of several activities and strategies for each way of thinking that future researchers and collaborators may find useful. Third, the SEFT ways of thinking framework was adapted for EER with the hope that researchers can use this instrument and build on it to study different ways of thinking in further detail. There is much to be learned about ways of thinking; to identify and confirm relationships between factors, between each way of thinking, and even examining a higher order model. Fourth, identifying underlying factors that inform ways of thinking and contribute to the success of EER projects could also guide the decision-making for policymakers and funding agencies. Finally, though the instrument was developed in the context of EER, it describes a spectrum of collaborative research activities at a broad level. We expect that the instrument may be relevant for a wider variety of STEM contexts or interdisciplinary research collaborations and encourage other researchers to examine its usefulness in other contexts.

Limitations and Future Research

As with any research, there are limitations associated with this study. This study is one of the first to examine ways of thinking related to EER. The scope of the study and survey items were intentionally limited to get a preliminary sense of the nature of the futures, values, systems, and strategic ways of thinking used in collaborative EER projects. With the initial findings on hand, future research could explore each way of thinking in further detail. As part of our future plans, we will revise and write additional items to strengthen the factors and constructs.

Another potential limitation is that lesser number of early career researchers who participated in the survey (Table 4.2). The EFA of the ways of thinking could yield different results for a different sample of PIs. Future research could investigate differences in ways of thinking among various groups (e.g., experience or discipline). We intentionally refrained from collecting gender data from participants for this study believing that this demographic would not likely have an impact on responses, but now plan to examine if gender influences these four ways of thinking in future research.

An immediate follow-up plan is to refine the survey items and constructs through multiple iterations and a survey inquiry. In the future, a confirmatory analysis should verify the correlated factors with a possibility of cross loadings among measures. A higher-order model of ways of thinking could also be explored in the future to further advance the knowledge base regarding 'EER ways of thinking'. Overall, findings of this study should be considered as preliminary. Replication of this empirical investigation with other samples would help strengthen the determination of the construct validity of futures, values, systems, and strategic thinking for EER in different contexts.

Conclusion

The need for innovation in engineering education necessitates research on ways of thinking. We sought to gain this understanding based on four specific ways of thinking including futures, values, systems, and strategic thinking. The study builds on the existing body of knowledge regarding these ways of thinking, while initiating a first step toward an EER ways of thinking model. Few such models exist that are specific to EER. We believe the resulting model could serve as an organizing and motivating structure to frame decisions throughout all engineering education endeavors.

CHAPTER 5

WAYS OF THINKING ACROSS THREE STUDIES

The purpose of this chapter is to look across the three studies that constitute this dissertation and provide a summary, discuss overall results, and share a vision for how this work might be further developed in the future. In the sections that follow, I first provide a brief summary of the overall research project. Next, I review the findings within and across the three studies, connecting to prior research and potential implications. I then discuss validity and trustworthiness as they relate to this research project. Finally, I present the future avenues to apply and extend this research and share my closing thoughts. Since this chapter is part of the dissertation, the citations are carried forward from the first chapter however, the abbreviations are redefined to help the reader.

Summary of the Research Project

There are very few models or theories that have been developed on ways of thinking specifically for engineering education. This exploratory research sought to lay the foundation for a conceptual ways of thinking framework and a scale for Engineering Education Research (EER). The scope of the study was confined to the collaborations between and among engineering and social sciences researchers (NSF, 2017). The research was conducted using a three-study design wherein each study informed the next to achieve a collective, coherent understanding of the ways of thinking as they are contextualized within EER.

The first study adapted the four ways of thinking proposed under the Sustainability Education Framework for Teachers (SEFT) – futures, values, systems, and strategic thinking – to the context of engineering education by drawing upon existing literature as well as an empirical inquiry. Concrete abilities pertaining to engineering education and research were identified for each way of thinking from an extensive literature review. The empirical inquiry included interviews with eight engineering and social sciences research collaborators to explore conceptualizations of futures, values, systems, and strategic thinking within authentic EER projects. Synthesis of the literature review combined with the results of the empirical investigation validated the applicability of ways of thinking perspectives to the EER context and set the stage for the next, mixed methods phase of this research.

Using a qualitative design, the second study explored both deductively and inductively what and how researchers who work on engineering education projects think and do about futures, values, systems, and strategic thinking. Nine engineer-social scientist dyads were interviewed and team meetings were observed. The data were analyzed to identify repeated and salient themes which produced detailed and contextualized perspectives of different ways of thinking across participants. I also examined applications as well as challenges of implementing the four ways of thinking. The results were used to build a survey for the third and final study.

The third study entailed development of an original survey instrument which was completed by 111 engineering education researchers across the nation. The goal was to understand the nature of ways of thinking on a larger scale, specifically in the context of interdisciplinary EER. Survey data were first analyzed for descriptive statistics, correlations, and reliability to establish factorability. Next, an exploratory factor analysis (EFA) was conducted to uncover the underlying dimensions of futures, values, systems, and strategic thinking used in collaborative EER.

Results of the qualitative and quantitative studies were examined together to triangulate and identify convergent and divergent evidence across the three studies (Greene, 2007). Triangulated results indicated that researchers were thinking about educating future workforce as well as the future research practices and outcomes. However, the research practices were built on more short-term thinking. Although results of values thinking suggested clear presence of diversity and inclusion values as well as personal values, the research or teaching related values did not converge completely. This could be due to multiple different interpretations of values thinking and priorities of values across participants. Results also suggested weaknesses regarding systems thinking and failed to uncover underlying dimensions of systems thinking. Strategic thinking was perceived as the most relevant construct for EER which, in addition to research related strategies, also had a personal component. In the following section, I discuss these results expanding the conclusions of each individual study.

Discussion of Results

This research is one of the first scholarly explorations of ways of thinking in the field of engineering education. The research attempted to appraise ways of thinking used in collaborative EER using the SEFT as a guiding lens. The findings revealed a variety of conceptualizations and various dimensions of futures, values, systems, and strategic thinking among EER collaborators.

Futures Thinking

Both qualitative and quantitative findings indicate that researchers' futures thinking concentrated on two related but distinct aspects: 1) engineering education that prepares the future workforce, and 2) research practices and outcomes. These two broad themes are indicative of the distinction researchers made between the teaching and learning related thinking and research related thinking. With EER established as an area of scholarly pursuit or a distinct discipline, many researchers differentiate between the two (Froyd, & Lohmann, 2014; Haghighi, 2005). The research community is also trying to take EER to the next level, beyond individual classroom studies, to look at the broader engineering education system, policies, and institutionalization (Jesiek et al., 2010; Johri & Olds, 2014, McKenna et al., 2014). The distinction in ways of thinking made by participants, in separate themes for education and research, suggests an alignment with the current conversations taking place in the field.

The findings also reveal a focus on what will happen next as opposed to what *could* happen, suggesting an influence of short-term thinking on research practices. While some participants admitted that looking into the future was difficult, others relied on incremental thinking, going from one project to the next. Observations also confirmed anticipatory research approaches built on short-term thinking. Prior research has alluded to the presence of short-term thinking in the field (Lande & Leifer, 2010; McKenna et al., 2014; NAS, 2007). One must wonder if grant funding has created counterproductive secondary effects (Bloch & Sørensen, 2014). The cycle of dependency on grant funding could make it difficult for researchers to engage in more long-term thinking. While grant funding will always have its place, there is an implication here for industry, administrators, and funding agencies. Agencies could consider funding longer-term projects like ERC's that get reevaluated and could go as long as 10 years. There is also an opportunity for impact investing (Bugg-Levine & Emerson, 2011) for industry considering the social impacts of tackling complex engineering education problems.

Overall, the results on futures thinking suggest the need for long-term, imaginative thinking that informs current education and research practices to actualize transformation.

Values Thinking

Values thinking, while acknowledged as relevant by the participants, diverged in meaning and adoption over a broad spectrum. Qualitative inquiry suggested that researchers' values thinking was not only about values of diversity and inclusion but also pedagogical values, research values, design values, and personal values of research and collaboration. The quantitative analysis yielded fairly clean loading patterns for diversity and inclusion as well as personal value. A research values-related factor did not converge, suggesting a need for more items.

Values and culture go together (Schwartz, 1997). Institutional culture, departmental culture, and culture of the discipline or field play a role in how values are perceived (Boden & Borrego, 2011; Hofstede, 1998). Since the survey was designed based on qualitative data gathered from one institute, it is possible that certain items were deemed of lesser value by participants of 64 other institutes. The multiple interpretations and varied perceived importance of values also suggest the need for the field to define its values. Prior research has indicated a continued sense of ambiguity about the identity of EER as a field and values that inform research practices (Heywood, 2014; Jesiek et al., 2009).

Another interesting observation from the quantitative inquiry on values thinking was the very high correlation found between the items related to diversity and inclusion. Diversity and inclusion are two different concepts (Morely, 2018; Taylor, 2015). Researchers are just beginning to differentiate between these two highly correlated constructs. The higher correlation may suggest the need to create awareness regarding the differences between the concepts of diversity and inclusion. Overall, the results emphasize the need for further research on values thinking to shed light on the value-driven professional practices in the field.

Systems Thinking

Systems thinking was another construct where qualitative and quantitative findings did not completely converge. The qualitative findings suggested weaknesses in engaging with broader systems thinking that takes the “30,000-foot” perspective of the whole engineering ecosystem (McKenna et al., 2014). While participants recognized the concepts of elements, sub-systems, interdependencies, and cascading effects that are associated with systems thinking (Kellam et al., 2008; Spector & Davidsen, 1997), they were thinking about these concepts in the contexts of their local projects. Conceptualizations were less depictive of the systems thinking regarding broader problem-solving taking an expansive view of the ecosystem.

To further explore this discrepancy, the survey intentionally added items regarding the larger engineering education system; specifically mentioning the K-12 system, ABET (formerly known as the Accreditation Board for Engineering and Technology), funding agencies, and industry as other sub-systems in order to convey the bigger context (Godfrey et al., 2014; Kellam et al., 2008; McKenna et al., 2014). It was expected that participants will differentiate between the two contexts; however, participants did not differentiate between the local level systems and the larger ecosystem. The EFA resulted in one factor that captured the systems thinking from all levels. While items will need to be revised for specificity, there is also an implication here for funding agencies to use grant solicitations for fostering broader systems thinking among researchers.

Strategic Thinking

Results of qualitative and quantitative inquiries on strategic thinking converged. Conceptualizations of strategic thinking regarding positioning of research projects, strategic approaches of problem solving, consensus-building with stakeholders, managing resources, and generally laying the blue-print for a research project indicated that participants were thinking about research related strategies. The other two identified themes from the qualitative data, collaboration strategies and growth strategies, suggested another aspect of strategic thinking that was focused on personal strategies. The survey analysis confirmed these two broad categories of strategic thinking when EFA results yielded two clean factors of research strategies and personal strategies. Given that this research project was situated in the context of interdisciplinary collaborations, a distinct factor related to collaboration strategies to achieve personal and professional growth was likely to emerge. This finding parallels prior research on interdisciplinary collaborations that has identified multiple personal and relational strategies used by researchers to identify collaborators, to deal with epistemological differences between disciplines, and to sustain their collaborations (Borrego & Newswander, 2008; Lattuca, 2001; Miller & Mansilla, 2004). Overall, strategic thinking was perceived as a readily identifiable and the most important way of thinking by all participants.

Integrated Ways of Thinking

While this research attempted to examine each of the futures, values, systems, and strategic thinking individually, these ways of thinking can and should be used in conjunction with one another to analyze and consider engineering education problems and solutions. Together they present a networked approach to strengthen an EER inquiry. For example, when a diversity or inclusion related question focused on values thinking is used in conjunction with systems thinking, it creates a more robust inquiry which could have a larger impact at different scales in the engineering education system. Futures, values, systems, and strategic thinking, when considered in isolation, offer organizing principles for questioning, researching, and reflecting in interpersonal, interdisciplinary situations. When combined, they build capacity for researchers to 1) understand the broad and complex nature of engineering education challenges, 2) conceptualize problem-oriented, solution driven studies considering long-term impact, 3) situate project proposals considering value addition to the system, and 4) effectively execute projects to achieve the desired goals. Together the four ways of thinking embody the knowledge, skills, and attitudes necessary for problem solving with respect to complex engineering education challenges.

Implications

Findings of this research translate to a number of implications for policy and practice. An understanding of how engineering education researchers think regarding the needed changes in the system could be helpful in setting the future direction of proposal calls and informing the design of professional development workshops. This overall research project shed light on the following: 1) more focus on short-term futures thinking, 2) varied interpretations of values and diversity and inclusion considered as equivalent, 3) weaknesses associated in broader systems thinking, and 4) higher perceived importance of strategic thinking. These findings could inform how funding agencies develop future programs and request for proposals. For example, federal funding agencies like the NSF could devise grant solicitations that foster broader systems thinking or create further awareness regarding the concepts of diversity and inclusion. Leading agencies and professional organizations such as the National Academy of Engineering or the American Society for Engineering Education (ASEE) could design and promote workshops that engage researchers in scenario-building activities and long-term futures thinking. The workshops for the *Engineer of 2020* project (NAE, 2004, 2005) are a great example of fostering long-term futures thinking.

The findings also have implications for practices of research as well as teaching. To bring transformation in the existing system, researchers need to think about how their models, practices, and outcomes might actually influence the larger engineering community. Considering the importance participants placed on the infrastructure for adoption of research outcomes, researchers should also think early on about how their models and practices could be adopted and involve administrators in collaborative work to advance the state of the art in education.

A few participants indicated that futures, values, systems, and strategic thinking together represented what "collectively an interdisciplinary team should strive to achieve or brainstorm under." There is an implication here for future collaborators to use the ways of thinking model as a tool to situate their projects considering the broader system and long-lasting impact. The abilities listed under each way of thinking could be helpful to engineering or social sciences researchers who are planning to collaborate.

This research also provided valuable insight into real-world interdisciplinary projects. Interpersonal relations, mutual trust, and shared priorities are inevitable personal aspects that go together with any collaborative work. Faculty can increase their awareness of what counts as value contribution in other disciplines in order to find collaborators with complementary expertise, engage in meaning-making, and ultimately create value for all stakeholders.

Finally, there is a direct link of any EER to engineering classrooms. The ways of thinking findings also provide guidance for engineering educators to prepare change agents in a broader social context (Jamison et al., 2014). Given the importance participants placed on design and social justice, faculty should create associations between moral values and technical subjects (McCuen, 1992; Vesilind, 1991). They should engage students in considering the unintended consequences of their designed solution (Wiek et al., 2011b) and "increase student awareness of the societal impact of their chosen profession" (Borrego & Newswander, 2008, p. 133).

In sum, this research has highlighted the multitude of possibilities for supporting the four ways of thinking as well as implementing them in practice. Table 5.1 lists the implications and recommendations for various stakeholders.

Table 5.1

Implications for Policy, Research, and Teaching

Stakeholder	Recommendation
Funding agencies and professional societies	• Design and facilitate workshops or grant solicitations that foster broader systems thinking that considers other sub-systems such as the K-12 system, industry, ABET, and international students • Design and facilitate workshops that engage researchers in scenario-building and imagination activities to foster long-term futures thinking • Design and facilitate workshops or grant solicitations that increase awareness of the differences between diversity and inclusion. • Consider long-term grant solicitations that remove the immediate dependency on funding and allow researchers to conceptualize transformative and even disruptive mechanisms considering long-term futures and impacts
Administrators	• Encourage adoption of research outcomes by arranging for opportunities of engagement between researchers and practitioners
Researchers	• Consider writing proposals that would continue to be sustained into the future, even after the funding had expired • Conceptualize projects that would result in a model that could be applied in many different settings and used by other institutions • Consider involvement of administrators to provide infrastructure, change policies, and facilitate adoption of research
Collaborators	• Consider complementary expertise, shared values, and alignment of priorities when selecting research partners • Increase awareness of what counts as value contribution in other fields to enter a mutually beneficial interdisciplinary partnership
Faculty	• Engage students in imagining possible futures • Discuss unintended consequences of engineered solutions making connections between technology and societal impacts

Limitations

In this section, I discuss the limitations of this research. First, ways of thinking is a complex phenomenon and poses a potential challenge associated with parsing out each of the specific ways of thinking. I worked to overcome this challenge by implementing a sequence of studies, building on findings, and using both qualitative and quantitative methods to assess the phenomenon. Qualitative interviews were conducted in a dyad to gather more complete and balanced insights into participants' ways of thinking. Dyadic interviews expand coverage of the research topic as participants interact, differentiate their thoughts, and talk about ideas that might not have occurred to them individually

(Morgan, Eliot, Lowe, & Gorman, 2016). Observational data was also collected to gather objective insights for triangulation (Creswell, 2013).

The qualitative data, while collected across multiple heterogeneous EER projects, was limited to projects being conducted at one particular institution. The institutional culture could influence researchers' ways of thinking (Boden & Borrego, 2011); however, collecting interview and observational data from researchers at various institutions was beyond the scope of this research. For an exploratory inquiry, it was appropriate to limit the scope and gain detailed contextualized perspectives and deep understanding on ways of thinking in participants' actual voices and meting discussions (Flick, 2014).

Another limitation of the qualitative inquiry could be the researcher's subjectivity (Creswell, 2014; Tracy, 2013). The qualitative results that informed the survey represent my interpretation of the data. To evaluate the accuracy of the interpretations and to ensure credibility, inter-rater reliability (Landis & Koch, 1977) was established among co-authors, and member-checking with study participants was performed at multiple stages (Creswell, 2013).

The quantitative inquiry was limited due to the use of a nonprobability sample and a restricted number of survey items under each way of thinking. A nonprobability sample lessens the external validity (Fowler, 2002; Weisberg, 2005); however, the scope of the quantitative inquiry and survey items were intentionally limited to get a preliminary sense of the ways of thinking used in collaborative EER projects. If additional items had been included, EFA for values thinking might have resulted in a three-factor solution to match the qualitative results. Future work will include items to strengthen the factors and constructs for each way of thinking and using a larger target population and resulting sample size.

Since the survey was built by converting the qualitative themes into Likert-scale items, the items may have been biased to confirm the hypotheses regarding each way of thinking. I tried to address this concern through multiple expert reviews and think aloud pilot sessions. Nonetheless, it should be noted that a survey instrument is inherently limited by its items and scales (Fowler, 2002) and self-report measures are susceptible to bias (Spector, 1994). I was able to reach a fair sample size and good participation rate. Moreover, interpretation of the survey results in conjunction with qualitative findings helped to mitigate the potential for bias.

Considering the overall design that includes dyadic interviews, observations, instrument validation processes, inter-rater reliability, member-checking, and the overall mixed methods approach to the series of studies addresses many research limitations and provides a comprehensive understanding of engineering education researchers' ways of thinking.

Future Research

This research was the beginning piece of a larger overarching goal of developing a ways of thinking framework for EER. To that end, future research could pursue multiple different inquiries that together will ultimately lead toward characterization of various ways of thinking with concrete abilities, knowledge, and attitudes.

An immediate follow-up to this research would be a second survey inquiry with refinement of items and scales. Values thinking and systems thinking not only require a revision of existing items but also additional items to confirm qualitative findings. Future research should also include a confirmatory factor analysis to examine the intricate web of relationships between and among the factors and scales of ways of thinking for EER. Another direction for future research considering the larger goal of framework development would include exploring additional ways of thinking (e.g., design thinking or entrepreneurial thinking) that might be pertinent to EER. This inquiry could be extended to a larger number of engineering education projects at other sites, including numerous international sites. This research was an initial attempt at understanding ways of thinking in the context of collaborative EER. Future research should consider deep qualitative inquiries using an ethnographic research design to further understand ways of thinking, in particular, values thinking that spanned a wide range of interpretations.

Finally, the results of this inquiry suggest that futures, values, systems, and strategic thinking align well with the overarching goals of the National Science Foundation's Engineering Research Centers (ERC) Program. The ERC program is not only futures oriented with systems approaches on different scales, but also embeds specific required education and diversity components and a robust strategic plan from the leadership team to avail and sustain funding, as I noted earlier. Future research could examine researchers' ways of thinking in the ERC context. Various scaffolding strategies that develop these ways of thinking among ERC students could also be explored.

Closing Thoughts

The current research represents a unique attempt that explored futures, values, systems, and strategic thinking in the context of EER collaborations. Given the emphasis from the funding agencies such as the NSF on ways of thinking and numerous references to ways of thinking in the literature, the purpose of this project was to provide an appreciation for ways of thinking perspectives along with an empirical account. This research shows that ways of thinking, often perceived as a theoretical concept, could and should be used in practice to innovate and inform EER. The overall research project contributes to the existing body of literature by articulating concrete abilities and describing authentic examples of applications and challenges of each way of thinking as they apply to EER. By exploring the underlying dimensions, this project also sets the direction for future research to refine the instrument and expand the empirical basis of the inquiry.

The challenges faced by the engineering education system are multifaceted and could use novel ways of thinking to address complex problems. The findings of this research build capacity for all stakeholders to explore whether it is possible to teach engineering in a different way, to bring systemic change, and to create an innovative and inclusive profession. I hope that the insights gained from this research and any future work related to this dissertation will inform the framing of decisions regarding problem/solution patterns of all engineering education endeavors.

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APPENDIX A

[IRB APPROVALS]

ASU Knowledge Enterprise Development

EXEMPTION GRANTED

Leanna Archambault
Division of Educational Leadership and Innovation - West
602/543-6338
Leanna.Archambault@asu.edu

Dear Leanna Archambault:

On 1/18/2017 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	Pilot Study on Engineering Education: Trends and Needs
Investigator:	Leanna Archambault
IRB ID:	STUDY00005554
Funding:	None
Grant Title:	None
Grant ID:	None
Documents Reviewed:	• IRB_Pilot_EnggEdu.docx, Category: IRB Protocol; • Pilot_EnggEdu_RecruitmentScript.pdf, Category: Recruitment Materials; • Pilot_EnggEdu_InterviewQ.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Pilot_EnggEdu_Consent Form.pdf, Category: Consent Form;

The IRB determined that the protocol is considered exempt pursuant to Federal Regulations 45CFR46 (2) Tests, surveys, interviews, or observation on 1/18/2017.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc: Medha Dalal
Wilhelmina Savenye

APPROVAL: MODIFICATION

Leanna Archambault
Division of Educational Leadership and Innovation - West
602/543-6338
Leanna.Archambault@asu.edu

Dear Leanna Archambault:

On 10/19/2017 the ASU IRB reviewed the following protocol:

Type of Review:	Modification
Title:	Pilot Study on Engineering Education: Trends and Needs
Investigator:	Leanna Archambault
IRB ID:	STUDY00005554
Funding:	None
Grant Title:	None
Grant ID:	None
Documents Reviewed:	• Pilot_EnggEdu_Consent Form.pdf, Category: Consent Form; • IRB_Pilot_EnggEdu.docx, Category: IRB Protocol; • Pilot_EnggEdu_RecruitmentScript.pdf, Category: Recruitment Materials; • Pilot_EnggEdu_InterviewQ.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions;

The IRB approved the modification.

When consent is appropriate, you must use final, watermarked versions available under the "Documents" tab in ERA-IRB.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc: Medha Dalal
Wilhelmina Savenye

APPROVAL: MODIFICATION

Leanna Archambault
Division of Educational Leadership and Innovation - West
602/543-6338
Leanna.Archambault@asu.edu

Dear Leanna Archambault:
On 2/13/2018 the ASU IRB reviewed the following protocol:

Type of Review:	Modification
Title:	Pilot Study on Engineering Education: Trends and Needs
Investigator:	Leanna Archambault
IRB ID:	STUDY00005554
Funding:	None
Grant Title:	None
Grant ID:	None
Documents Reviewed:	• Pilot_EnggEdu_Consent Form.pdf, Category: Consent Form; • Pilot_EnggEdu_RecruitmentScript.pdf, Category: Recruitment Materials; • IRB_Pilot_EnggEdu_revised for observations.docx, Category: IRB Protocol; • Observation protocol.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Pilot_EnggEdu_InterviewQ.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Pilot_EnggEdu_Consent Form_for observation.pdf, Category: Consent Form;

The IRB approved the modification.

When consent is appropriate, you must use final, watermarked versions available under the “Documents” tab in ERA-IRB.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,
IRB Administrator

cc: Medha Dalal
Wilhelmina Savenye
Adam Carberry

APPROVAL: MODIFICATION

Leanna Archambault

Division of Educational Leadership and Innovation - West Campus
602/543-6338
Leanna.Archambault@asu.edu

Dear Leanna Archambault:

On 9/21/2018 the ASU IRB reviewed the following protocol:

Type of Review:	Modification
Title:	Pilot Study on Engineering Education: Trends and Needs
Investigator:	Leanna Archambault
IRB ID:	STUDY00005554
Funding:	None
Grant Title:	None
Grant ID:	None
Documents Reviewed:	• Pilot_EnggEdu_Consent Form.pdf, Category: Consent Form; • EnggEdu_Consent Form_for Survey_v1.pdf, Category: Consent Form; • Survey.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • IRB_Protocol_EnggEdu_revised for survey.docx, Category: IRB Protocol; • EnggEdu_RecruitmentScript for Survey_v1.pdf, Category: Recruitment Materials; • Pilot_EnggEdu_RecruitmentScript.pdf, Category: Recruitment Materials; • Observation protocol.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Pilot_EnggEdu_InterviewQ.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); Pilot_EnggEdu_Consent Form_for observation.pdf; Category: Consent Form;

The IRB approved the modification.

When consent is appropriate, you must use final, watermarked versions available under the “Documents” tab in ERA-IRB.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc: Medha Dalal,
Wilhelmina Savenye
Adam Carberry

APPENDIX B

SURVEY INSTRUMENT

Survey: Ways of Thinking for Engineering Education Research

Welcome and Informed Consent

Thank you for participating in this survey regarding ways of thinking used to address complex challenges in the engineering education system. We value your response. We will first present the definitions of four specific ways of thinking that include **futures, values, systems and strategic thinking,** and then ask you a few questions regarding each of these ways of thinking. Your responses will help the researchers better understand ways of thinking approaches that are used for interdisciplinary engineering education research. The survey will take approximately 15 minutes to complete. Please note that you will not be able to go back after completing a page.

You must be age 18 or older to participate. Your responses will be anonymous. You have the right not to answer any question. There are no foreseeable risks or discomforts to your participation. The aggregated results of this study may be used in reports, presentations, or publications. If you have any questions concerning the research study, please contact the research team: Medha Dalal (medha.dalal@asu.edu), Dr. Adam Carberry (adam.carberry@asu.edu) or Dr. Leanna Archambault (leanna.archambault@asu.edu). If you have any questions about your rights as a participant in this research, or if you feel you have been placed at risk, you can contact the Chair of the Human Subjects Institutional Review Board, through the ASU Office of Research Integrity and Assurance, at (480) 965-6788.

If you wish to participate in the Amazon gift card drawing, a separate link at the end of the survey will take you to a different form where you can provide your email independent of the survey responses. Clicking on the Next button below will be considered as your consent to participate in this survey. We sincerely thank you for taking the time to complete the survey.

Values Thinking

Values thinking broadly involves one's philosophical, social, and cultural beliefs. It includes understanding the concepts of ethics, equity, and social justice in the context of different cultures, acknowledging varying perspectives, and making decisions accordingly.

1. a) In your engineering education research project, do you believe you have used values thinking?

- ○ Yes [If selected] 1. b) Please describe an example from your project that you believe involved values thinking
- ○ No [If selected] 1. b) Why do you think you have not?
- ○ Maybe [If selected] 1. b) Please describe an example from your project that you think may have involved values thinking.

2. How important are/were following actions considering values (cultural, intellectual, social, monetary, etc.) in the context of your research project?

	Not at all important	Somewhat important	Moderately important	Quite important	Extremely important
a) Valuing diversity in the profession	○	○	○	○	○
b) Valuing inclusion in the profession	○	○	○	○	○
c) Reconciling personal values with those of your collaborator(s)	○	○	○	○	○
d) Aligning personal values with the engineering education research you pursue	○	○	○	○	○
e) Aligning societal values with the engineering education research you pursue	○	○	○	○	○
f) Improving engineering teaching for the purpose of addressing the needs of all students	○	○	○	○	○
g) Considering the heterogeneity of the end user(s) when creating a solution (e.g., differences in users' gender, ethnicity, age, experience, etc.)	○	○	○	○	○
h) Using research methodologies that highlight the value of context	○	○	○	○	○
i) Creating new knowledge through engineering education research	○	○	○	○	○

If you have any comments about the items or your response to the items above, please include them below.

____

Futures Thinking

Futures thinking is about anticipatory approaches to understanding and preparing for future changes, problems, and solutions in the field of engineering education. It involves an understanding of how today's solutions could impact the field in the immediate, mid-range, and/or long-term time frames.

3. a) In your engineering education research project, do you believe you have used futures thinking?

○ Yes [If selected] 3. b) Please describe an example from your project that you believe involved futures thinking

○ No [If selected] 3.b) Why do you think you have not?

○ Maybe [If selected] 3. b) Please describe an example from your project that you think may have involved futures thinking.

4. How important are/were the following actions considering futures in your research project?

	Not at all important	Somewhat important	Moderately important	Quite important	Extremely important
a) Engaging in scenario-building activities to imagine what engineering education might look like in the future	○	○	○	○	○
b) Preparing students to become future professionals	○	○	○	○	○
c) Preparing students to become contributing citizens of society	○	○	○	○	○
d) Changing curricula to include course(s) that are needed but not currently taught in the programs	○	○	○	○	○
e) Changing the teaching practices of engineering faculty through professional development	○	○	○	○	○
f) Selecting research projects that have a potential for long lasting impact	○	○	○	○	○
g) Adopting research practices to drive transformational change (e.g., examining the past, understanding trends, identifying problems, and developing focused questions)	○	○	○	○	○
h) Encouraging administrators to provide necessary infrastructure to support grant projects after external funding has expired	○	○	○	○	○
i) Focusing on ways to improve the translation of research to practice	○	○	○	○	○
j) Engaging in short-term thinking to impact the immediate future	○	○	○	○	○

If you have any comments about the items or your response to the items above, please include them below

Systems Thinking

Systems thinking broadly involves considering holistic approaches to problem-solving. It is about understanding and/or analyzing the complexity of various components and subcomponents, as well as their interrelationships in the overall ecosystem.

5. a) In your engineering education research project, do you believe you have used systems thinking?

- ○ Yes [If selected] 1. b) Please describe an example from your project that you believe involved systems thinking
- ○ No [If selected] 1b) Why do you think you have not?
- ○ Maybe [If selected] 1. b) Please describe an example from your project that you think may have involved systems thinking.

6. How important are/were the following actions considering the role of systems in your research project?

	Not at all important	Somewhat important	Moderately important	Quite important	Extremely important
a) Recognizing that a given problem may exist at different scales (local or global)	○	○	○	○	○
b) Integrating different aspects of the project to ensure synergy across all components	○	○	○	○	○
c) Recognizing the implications of the project on all the stakeholders, even those not directly engaged as users, researchers, or collaborators	○	○	○	○	○
d) Recognizing the interdependence of components within the whole engineering education system (e.g., K-12 system, international partnerships, accreditation bodies, funding agencies, industry, professional bodies, etc.)	○	○	○	○	○
e) Uncovering interactions of elements within the engineering education system for a given problem	○	○	○	○	○
f) Thinking about implications of your research in the larger context of the engineering education ecosystem	○	○	○	○	○
g) Identifying cascading effects of a solution on other components within the engineering education system	○	○	○	○	○
h) Formulating problems considering the dynamic nature of the education system	○	○	○	○	○

If you have any comments about the items or your response to the items above, please include them below.

Strategic Thinking

Strategic thinking is the ability to create a plan of action to achieve the desired vision. It involves envisioning long-term goals and objectives, collectively developing a plan, and considering appropriate courses of action and resource allocation that could lead to innovation in addressing today's challenges.
7. 1. a) In your engineering education research project, do you believe you have used strategic thinking?

- ○ Yes [If selected] 1. b) Please describe an example from your project that you believe involved strategic thinking
- ○ No [If selected] 1b) Why do you think you have not?
- ○ Maybe [If selected] 1. b) Please describe an example from your project that you think may have involved strategic thinking.

8. How important are/were the following actions considering strategies in the context of your research project?

	Not at all important	Somewhat important	Moderately important	Quite important	Extremely important
a) Developing strategies to position your research within larger initiatives of your or your collaborator's organization	○	○	○	○	○
b) Employing strategies to convey the importance of your research to various audiences	○	○	○	○	○
c) Creating an overall plan for what is involved in the project	○	○	○	○	○
d) Developing strategic courses of action to execute the project	○	○	○	○	○
e) Using creative approaches to strategically address a challenging situation	○	○	○	○	○
f) Using evaluation strategies to capture the impact of your research	○	○	○	○	○
g) Improving strategies based on lessons learned at various stages of the project	○	○	○	○	○
h) Applying strategies that seek to strengthen your interdisciplinary collaboration	○	○	○	○	○
i) Developing strategies that contribute to your professional growth (e.g., diversifying for broader learning, relationship building, etc.)	○	○	○	○	○

If you have any comments about the items or your response to the items above, please include them below.

Demographics

9. Please select the programs you are associated with at your institution from the choices below. (select all that apply)

__Engineering
__Education
__Learning Sciences
__Psychology
__Engineering Education
__Other _____________

10. For how many years have you been teaching in higher education? Please write the number below.

____

11. For how many years have you been involved with interdisciplinary engineering education research? Please write the number below.

____

12. Please select the job or title that best describes your current position at your institute.

__Professor
__Associate professor
__Assistant professor
__Adjunct faculty
__Clinical faculty
__Other ___________

13. What is/was your role on the engineering education research project?

__Project PI
__Social Science Researcher Co-PI
__Engineering Education Researcher Co-PI
__Unspecified Co-PI
__Senior Personnel
__Other ____________

APPENDIX C

SURVEY EMAIL COMMUNICATION

PRE-NOTIFICATION EMAIL

Sent on week 1, day 1

Dear Professor,

You are among a small, select group of researchers invited to take a survey as an awardee of the Engineering Education Grant Name grant under the Professional Formation of Engineers program at NSF. The survey explores ways of thinking that may inform researchers' decision-making for engineering education challenges.

Why your participation is important

This survey examines ways of thinking to better understand how researchers such as yourself think, act, and engage with transformational challenges of the engineering education system. The findings will help collaborators re-conceptualize and situate their future research proposals. An understanding of how engineering education researchers think regarding the transformation within the system could also be helpful in setting the future direction of grant-funded proposal calls.

When: In two days, the survey link will be sent to your email.
How long: The survey will take about 15 minutes to complete.

Your responses will be anonymous. Only aggregated results will be used in academic publications. As a token of our appreciation for completing the survey, you can enter to win one of four $25 Amazon e-gift cards by entering your email on a separate link at the conclusion of the survey.

If you have any concerns, please email medha.dalal@asu.edu. We sincerely thank you for your support and for all the work you do for students and the field of higher education.

Please check your inbox in two days for the survey link!

Sincerely,

Medha Dalal, Doctoral Candidate, Mary Lou Fulton Teachers College
Adam Carberry, Associate Professor, The Polytechnic School
Leanna Archambault, Associate Professor, Mary Lou Fulton Teachers College
Arizona State University

Survey Link Email
Sent on week 1, day 4

Dear Professor,

We wrote you a few days ago because you are among a small, select group of Engineering Education Grant Name awardees invited to take part in a survey for engineering education research. As a reminder, the survey explores ways of thinking for addressing complex challenges in the engineering education system.

Your name was identified through a search of the NSF database. It is only by hearing from as many awardees as possible that we will be able to have an accurate picture of how different ways of thinking may affect engineering education research. We strongly encourage you to participate in the survey.

Please follow this link to the survey:
${l://SurveyLink?d=Take the survey}
Or copy and paste the URL below into your internet browser:
${l://SurveyURL}

What is involved?

- Complete a survey that takes about 15 minutes within the next few weeks.
- Your responses will be anonymous. Only aggregated results will be used in academic publications.
- After completing the survey, you can enter to win one of four $25 Amazon e-gift cards being given away as a thank you. A separate form at the conclusion of the survey will ask for your email. The survey responses will not be linked to the email address.

If you have any concerns, please email medha.dalal@asu.edu. We sincerely thank you for your support and for all the work you do for students and the field of higher education.

Again, click this link to: ${l://SurveyLink?d=Take the survey}

Sincerely,

Medha Dalal, Doctoral Candidate, Mary Lou Fulton Teachers College
Adam Carberry, Associate Professor, The Polytechnic School
Leanna Archambault, Associate Professor, Mary Lou Fulton Teachers College
Arizona State University

To opt out of future emails ${l://OptOutLink?d=click here}

Reminder Email 1
Sent on: week 2, day 4

Dear Professor,

This is a reminder that you are among a small, select group of Engineering Education Grant Name awardees invited to take part in this 15-minute survey. The survey explores ways of thinking for addressing complex challenges in the engineering education system. It is only by hearing from researchers like you that we will be able to understand the ways of thinking approaches that could lead to transformation in the engineering education system. As a thank you, after completing the survey, you can enter to win a $25 Amazon e-gift card.

Please follow this link to the Survey: ${l://SurveyLink?d=Take the Survey}

Or copy and paste the URL below into your internet browser:
${l://SurveyURL}

Your responses will be anonymous. Only aggregated results will be used in academic publications. The survey is available for just a few weeks,
so **please click** ${l://SurveyLink?d=**this link**} **to access the survey.**

If you have any concerns, please contact medha.dalal@asu.edu. We sincerely thank you for your support and for all the work you do for students.

Sincerely,
Medha Dalal, Doctoral Candidate, Mary Lou Fulton Teachers College
Adam Carberry, Associate Professor, The Polytechnic School
Leanna Archambault, Associate Professor, Mary Lou Fulton Teachers College
Arizona State University

${l://OptOutLink?d=Click here to unsubscribe}

Reminder Email 2
Sent on: week 3, day 4

Dear Professor,

In our previous emails, we wrote to let you know you were selected as part of a special group of awardees invited to take part in this 15-minute survey. The survey explores Engineering Education Grant Name PI/Co-PI's ways of thinking for addressing complex challenges in the engineering education system.

You are receiving this email because: 1) you have clicked on the survey link and started filling out your answers but not completely finished, or 2) you have yet to participate in the survey. Soon this survey is coming to a close. We are hoping to hear from as many awardees as possible to get an accurate depiction.

Please help by taking the survey today. The link below will take you where you left off.

${l://SurveyLink?d=**Take the Survey**}

Or copy and paste the URL below into your internet browser:
${l://SurveyURL}

The survey is available for just one more week, so be sure to fill it out soon. The survey is anonymous. After completing the survey, you can enter to win a $25 Amazon e-gift card on a separate link. If you have any concerns, please send email to medha.dalal@asu.edu. We sincerely thank you for your support and for all the work you do for students and higher education.

Again, click this link to access the survey: ${l://SurveyLink?d=**Take the Survey**}

Sincerely,
Medha Dalal, Doctoral Candidate, Mary Lou Fulton Teachers College
Adam Carberry, Associate Professor, The Polytechnic School
Leanna Archambault, Associate Professor, Mary Lou Fulton Teachers College
Arizona State University

${l://OptOutLink?d=Click here to unsubscribe}

Reminder Email 3
Sent on: week 4, day 4

Dear Professor,

We want to offer one last opportunity to participate in the survey of Engineering Education Grant Name awardees. The survey explores PI/Co-PI's ways of thinking for addressing complex challenges in the engineering education system. We selected a special group of NSF awardees to take this survey and really want to hear from you regarding collaborative engineering education research.

Please help by taking the survey today.

${l://SurveyLink?d=**Survey link**}

Or copy and paste the URL below into your internet browser:
${l://SurveyURL}

What's involved?

- The survey takes about 15 minutes to complete.
- Your responses are anonymous.
- The survey **closes on November 25, 2018**, so please fill it out now.
- At the end of the survey, please enter your email address on a separate link, independent of your survey responses, for the $25 Amazon e-gift card drawing.
- Results will be used for academic publications.

If you have any concerns, please send email to medha.dalal@asu.edu. We sincerely thank you for your support and for all the work you do for students.

Again, click this link to access the survey: ${l://SurveyLink?d=Take the Survey}

Sincerely,
Medha Dalal, Doctoral Candidate, Mary Lou Fulton Teachers College
Adam Carberry, Associate Professor, The Polytechnic School
Leanna Archambault, Associate Professor, Mary Lou Fulton Teachers College
Arizona State University

${l://OptOutLink?d=Click here to unsubscribe}

End of Survey 'Thank You' Email

Dear Researcher,

Thank you for participating in our ways of thinking survey. We had a great response rate. If you are interested in results, please contact me and I'll be happy to share the findings with you in couple of months.

Based on the random drawing, some of you should have received an email from amazon regarding $25 e-gift card. Congratulations!

We genuinely value and appreciate your participation.

Thank you once again and happy holidays,
Medha Dalal, Doctoral Candidate, Mary Lou Fulton Teachers College
Adam Carberry, Associate Professor, The Polytechnic School
Leanna Archambault, Associate Professor, Mary Lou Fulton Teachers College
Arizona State University

Follow the link to opt out of future emails:
${l://OptOutLink?d=Click here to unsubscribe}