Engineering Uncertainty: A qualitative study on the way middle school teachers incorporate, manage and leverage the uncertainty of engineering design task

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Engineering Uncertainty: Managing Uncertainty While Teaching Engineering Design Tasks in a Middle School Classroom

Introduction

“*The future is no more uncertain than the present.*” - Walt Whitman

As people make decisions and solve problems in their professional and everyday lives, they continually face elements of uncertainty. However, schools rarely provide learning opportunities or environments that allow for uncertainty. Research has shown that teachers and curriculum tend to minimize or avoid uncertainty because it is perceived as increasing anxiety and lowering the quality of instruction.\(^1,2\) Instead, teachers overwhelmingly tend to focus on familiar, well-structured, or procedural tasks that are low in both ambiguity and risk.\(^3,4\)

With the integration of engineering in the Next Generation Science Standards (NGSS)\(^5\), uncertainty, which is an inherent aspect of engineering,\(^4-8\) may finally play a larger role in the K-12 education system. Due to this inherent uncertainty, K-12 engineering education holds the potential to provide students with opportunities to face problems with uncertainty and develop the abilities, mindset and strategies engineers use to tackle and overcome the uncertainty of ill-structured and complex problems. While the possibilities of K-12 engineering education are alluring, it is important to consider the new barriers, challenges and risks that teachers must face in creating learning environments where students deal with the uncertainty of ill-structured engineering problems. As schools begin integrating engineering into the classroom, it is important to explore if and how teachers are able to support students in dealing with uncertainty, while simultaneously managing the risks and challenges related to their own pedagogical uncertainty.

While there is substantial literature on the uncertainty of engineering as well as the pedagogical uncertainty teachers face, few researchers have addressed uncertainty as it relates to K-12 engineering education, and fewer still have directly observed teachers and students as they are faced with the uncertainty of an engineering design challenge. The purpose of this study is to explore uncertainty as it relates to integrating engineering into middle school science classrooms. Specifically, this study uses an exploratory case approach to look at one middle school science teacher, Janice (pseudonym), as she teaches a newly adopted engineering unit in her 7th grade science classroom. The guiding research questions for this study are: (1) what is the source of the uncertainty that the teacher and students experienced?; (2) what is the teachers’ perspective on her experience managing uncertainty?; and (3) how did the teacher deal with uncertainty?

Nature of Uncertainty in Engineering

As engineers work to solve open-ended and ill-structured problems they continuously face design decisions that are filled with ambiguity or uncertainty.\(^9\) Good designers, as Dym and his colleagues\(^5\) assert, must be able to handle uncertainty while tolerating the ambiguity that shows up in the iterative process of design as inquiry. While these and many other authors all accept uncertainty as an inherent part of engineering, the exact meaning and nature of this uncertainty
varies across the literature but is largely related to the fact that engineers solve ill-structured problems, that are complex, unpredictable, and dynamic. To conceptualize the uncertainty as it relates to the nature of engineering, this study extracts various elements from the literature. These elements include: (1) the uncertainty of interpreting the problem, constraints, and goals within a complex, open-ended situation; (2) the unpredictability of solving divergent problems that require the evaluation and judgment of many alternative solution paths; (3) the uncertainty of optimizing a design that satisfies the competing demands and constraints of the client as well as safety, economical, environmental, and ethical concerns; (4) the uncertainty of solving dynamic problems that require a person to constantly adjust, reevaluate and evolve as unanticipated problems arise; and (5) designing solutions within imperfect models and incomplete information that requires all engineers to reason through some degree of uncertainty. While these elements are described separately, they interrelate and overlap in how they factor into the uncertain nature of engineering.

The uncertain nature of engineering, as illustrated above, is a crucial aspect to the work of engineers. Therefore, engineers must learn to reason about and deal with this uncertainty in order to solve ill-structured problems. The most fundamental and overarching approach engineers use to reduce and manage uncertainty is the engineering design process, or what some refer to as design thinking. The engineering design process, which is defined as a purposeful, creative process that allows for many possible solutions and satisfying a specified set of constraints aids engineers in reducing and managing uncertainty. Dym and his colleagues explain how engineers use the design process as an iterative loop of divergent-convergent thinking to tolerate ambiguity by continuously exposing and considering various alternatives and converging on verifiable, “truthful” answers or solutions. Thus, the open, iterative elements of the design process allow engineers to reduce and manage the ambiguity of ill-structured problems by continually self-monitoring and adapting to changes in the problem space.

In addition to, or as part of, the design process, engineers use a variety of specific strategies to deal with uncertainty. Jonassen explains how ill-structured problem solving is not a linear process but instead requires successfully negotiating the uncertainty of divergent problems by constructing multiple problem spaces and then engaging in reflective practice or reflective conversation as they interpret and evaluate alternatives. These metacognitive strategies enable engineers to deal with uncertainty by continuously engaging in acts of self-evaluation, self-monitoring and reflection as they work through the engineering design process. The use of a collaborative environment has been found to help engineers reduce and manage uncertainty. Shin and his colleagues explain that working in teams allows engineers to reduce ambiguity by distributing the knowledge and skills and collectively making decisions. The ability to logically and persuasively argue for or against a decision helps reduce the ambiguity of evaluating and assessing various interpretations or perspectives throughout the design process.

Uncertainty in K-12 classrooms

Traditional school structure and curriculum tend to afford a kind of certainty that is seldom encountered in life outside school. This illusion of certainty robs students of the opportunity to foster the self-directed problem solving capabilities that are required to solve ill-structured problems, which are inherently ambiguous and unpredictable. Ford, similarly, found that
students, from a young age, can recognize uncertainty, engage in productive conversation about it and develop ways to deal with it. Manz\textsuperscript{21, 22} similarly states that uncertainty is an important part of scientific activity that leads to engagement in reasoning and understanding the usefulness of science practices as tools for sense making. Students, as Bolhuis\textsuperscript{15} states, “need to get used to, and to cope with, uncertainty, ambiguity, indefinite questions and problems” (p. 335).

While the research on K-12 engineering education is still developing, many studies have found that engineering tasks help young students develop critical thinking skills, engineering habits of mind, problem-solving skills and disposition, and a rich knowledge structure through engagement with complex ideas in discussion, reflection investigation, and experimentation.\textsuperscript{11, 17-23} Specifically, Roth\textsuperscript{23} found that engineering activities helped children learn to exploit the open-ended situations in a productive way, rather than being stifled by their attempts to find "right" answers. Roth’s findings highlight how students learned to use the flexibility of an engineering task to negotiate problems, solutions, and courses of action in creative ways. Engineering, therefore, has the potential to provide students with opportunities to experience and face problems with uncertainty and develop the abilities, mindset and strategies engineers use to tackle and overcome the uncertainty of ill-structured and complex problems.

Research has also shown engineering education to help teachers transform their instruction to a more integrated, project-based, hands-on and student-centered approach.\textsuperscript{18} However, other studies stress the challenges and risks that teachers encounter in creating and scaffolding learning environments that allow for uncertainty.\textsuperscript{1, 23, 24} These studies argue that teachers require training and support in dealing with unpredictability and the interpretive flexibility of student-centered engineering tasks.

**Pedagogical Uncertainty**

Teaching, like engineering, is inherently and inevitably uncertain. Teachers can never be certain how a lesson will go or what each student will learn from a lesson. Teachers can never be sure which strategy will be most successful, how to structure an activity, what to emphasize, or how much scaffolding to give a specific student or group of students. These uncertainties are tied to the very nature of teaching, which at its foundational level centers on human relationships and involves predicting, interpreting and assessing others’ thoughts, emotions, and behavior.\textsuperscript{2} Helsing\textsuperscript{2} adds that this pedagogical uncertainty is a result of the tension teachers face between competing commitments and the associated doubt of balancing the needs of individual students against the demands of the larger group, challenging students without defeating them, encouraging children’s overall development while guaranteeing academic progress and so on. Teachers are forced to make decisions where they must prioritize or make trade-offs between alternative commitments or responsibilities that they feel are equally important.

While increased knowledge and experience help reduce some of this pedagogical uncertainty,\textsuperscript{1} due to the intricacy of learning, the ingenuity of teaching, and the complexity of a classroom, uncertainty will always play a role in the act or art of teaching. Floden and his colleagues\textsuperscript{1, 25} outline four ways that uncertainty enters teaching. First, teachers face the uncertainty of assessing student understanding, which cannot truly be captured by any form of assessment. Second, teachers experience an uncertainty about the effects of their teaching. This is due to the
ambiguous and unpredictable links between teaching and learning, which leaves teachers unsure about the effects of their instructional strategies and how to enhance learning. The third way uncertainty enters teaching is linked to a teacher’s imperfect understanding of the content and the choices they face in deciding what content to cover and how to cover it within the limited time they are afforded. Fourth, uncertainty arises as teachers are confronted with a tension between respecting students' personal autonomy and exerting the intellectual and social authority required to maintain order and respect in a classroom.

In addition to the ways that uncertainty enters teaching, Doyle and Carter\textsuperscript{26} take a different perspective, explaining that the nature of an academic task influences uncertainty in a classroom. They claim that academic learning tasks elicit an element of uncertainty in the form of ambiguity and risk and attributed much of this uncertainty to the evaluative nature of schooling.\textsuperscript{3, 4} Due to this evaluative nature, Doyle\textsuperscript{4} states that a task’s novelty, cognitive level and instructional explicitness contribute to teachers’ pedagogical uncertainty. Doyle argues that novel, high-level tasks are overwhelmingly avoided for the sake of maintaining a smooth, manageable, and highly productive learning environment. This emphasis on productivity, which is highly valued in the U.S. school system, aims to maximize the type of learning that will result in the largest increases in testable knowledge over the shortest period of time. Consequently, teachers focus overwhelmingly on familiar work, and if novel or higher cognitive demanding tasks are given, risk and ambiguity are reduced and students are guided explicitly.\textsuperscript{4}

Like engineers, teachers work to reduce or manage uncertainty in their classrooms. However, unlike engineers, most teachers tend to deal with uncertainty by reducing it, ignoring it and avoiding it altogether.\textsuperscript{1, 3, 25, 26} Due to the negative effects, challenges and risk associated with ambiguity, many teachers tend to view uncertainty as a liability that generates negative emotional consequences, such as discomfort, anxiety, frustration and the feeling of being overwhelmed, for both the teachers and students. If teachers take this perspective, they feel threatened and engage, in what Helsing\textsuperscript{2} describes as, “self-defensive tactics” to protect their sense of control, their social and personal worth, and their authority (p. 1320). Many teachers who take this perspective mistakenly believe what McDonald\textsuperscript{27} refers to as the “conspiracy of certainty” in which they can find the one perfect way to teach. Helsing\textsuperscript{2} states that these teachers believe that uncertainty is an indication that they are not teaching well, and all uncertainties will vanish with time and increased expertise and experience. Teachers, who view uncertainty as a liability, react by reducing or avoiding uncertainty through pedagogical moves such as: compromising standards and assessment criteria, relying heavily on routine and strict rules and procedures, and acting conservatively by avoiding anything novel, demanding, or complex.\textsuperscript{2} Teachers can also deal with and reduce their uncertainty by increasing their knowledge of the subject matter, collaborating with colleagues, and voicing the risk, doubt and challenges they face.\textsuperscript{4, 25}

While the adverse view of uncertainty is majoritive, some teachers recognize and welcome uncertainty, as an asset or pedagogical tool to strengthen teaching and learning.\textsuperscript{2} Teachers who welcome uncertainty tend to understand that uncertainty can increase knowledge and expertise. They are accepting of the idea that there is no ultimate solution or perfect way to teach and that contradictions and chaos are part of teaching and becoming a better educator.\textsuperscript{2} Through inquiry and reflective practice, teachers with this mindset are willing to sustain a certain level of doubt
and uncertainty as a means for purposeful inquiry into their practice. Instead of avoiding or denying the uncertainty, they recognize that it can lead to better instruction and see the productive value and that it can be utilized to address problems of practice.

Beyond the intellectual and professional benefits of uncertainty, some teachers view ambiguity as a pedagogical tool for learning. Doyle\(^2\) explains that students respond to ambiguity and risk by negotiating with teachers to increase the explicitness of product specifications or reduce the strictness of grading standards. This negotiation process is not unlike the negotiation that engineers face in dealing with uncertainty. As students react by negotiating the uncertainty of a task, a teacher must make decisions about whether to reduce student uncertainty, or leverage uncertainty as a pedagogical tool for increasing understanding and developing the skills necessary to overcome the uncertainty. For example, Rowland\(^28\) found that uncertainty can prolong engagement and motivation and Doyle\(^4\) found that teachers are able to cushion the risk of uncertainty and encourage students to try more challenging open ended-tasks by providing opportunities for feedback or offering bonus points. Beyond a few studies, there is little research on how exactly teachers leverage uncertainty within an academic task as a pedagogical tool. This study aims to address the lack of research by specifically examining the uncertainties that manifest as a teacher integrates an engineering design task.

**Methods**

**Context.** This exploratory case study was done in the context of a grant-funded program toward the development of a middle school engineering curriculum and the accompanying professional development. The program is titled “Engineering 101: Middle school. (ENGR101MS)” This program aims to enhance the ability and efficacy of in-service middle school science teachers to integrate engineering into their classrooms. The goal of this curriculum was to create an engineering unit that connects to the locale of Arizona and meets the needs/constraints of middle school science teachers by aligning with both the Next Generation Science Standards\(^31\) and current state science standards. The unit, titled “The Great Arizona Ice House Challenge,” focused on testing and applying the scientific concept of heat transfer to design and to build a prototype of a more thermal efficient house that stays cool without the use of air conditioning or electricity. The unit had three main parts: (1) Introducing engineering and the scenario; (2) investigating the three types of heat transfer; and (3) designing, testing and presenting the final prototype. Through this sequence, students gathered data based on the three types of heat transfer and then used the data to inform their final design decisions. See below for examples from the “Great Arizona Ice House Challenge” unit. The final prototypes all worked well, using designs incorporating all three types of heat transfer. For example, all designs used lighter colors, utilized proven insulation materials, and put vents or holes to let heat out. The final results showed that most temperatures leveled off with temperature rising in three of the six groups by less than 5 degrees; much less than the control box. The winning group’s design won based on both temperature change and cost.
Participants. The study was conducted with a single teacher, Janice (pseudonym), who participated in a one-day professional development (PD) workshop. During this PD workshop Janice was exposed to, interacted with, and learned about engineering education and the specific engineering curriculum. Following the PD, she received a kit with the needed materials and digital copies of all handouts and support materials. Janice was asked by her administration to be part of the PD. She was selected for this study because she fit the criteria of being a middle school science teacher with little to no experience with engineering or engineering education. Janice is a 42 year old, white, female, 7th grade general science teacher in her first year of teaching. She has an elementary teaching certificate with endorsement for science and math in middle school. While Janice teaches five classes throughout the day, this study focuses on
Janice as she teaches the engineering unit to the 21 students in her first period general science class.

**Data collection and analysis.** Qualitative exploratory case study methods were employed to thoroughly explore the experience and interpretations of the participant. The exploratory case study approach was utilized to develop an in-depth interpretation of the intricate and complex experience and perspective of a teacher. The research design included three in-depth semi-structured interviews of the teacher participant: (1) pre-teaching interview, (2) ongoing interviews following each lesson, and (3) post-teaching interview. The study also included observations of the participant as she taught the engineering unit to her students. Field notes were used to collect data from the observations.

Data collected during the observations and interviews was coded using thematic analysis of the teacher’s interpretation of teaching an engineering unit. In this thematic analysis, data from the interviews and field notes were analyzed separately and then in parallel to look for similarities and differences and establish consistency. Through a process of open coding, key words or phrases were identified and then categorized into overarching themes. During this process, uncertainty was identified with specific phrases, words or body language, such as words or phrases akin to being “unsure,” and questions or disagreements related an indecision or doubt about design ideas, trade-offs, testing procedures or results. The initial categories include: experienced uncertainty related to the nature of engineering and pedagogical strategies for dealing with uncertainty. Using these initial categories and the literature on uncertainty, the data was reexamined, through a constant comparison method, to look for alternative explanations and new themes until final, consistent themes were determined. The final themes were categorized into four groups that are explained in the findings.

**Findings**

Findings are organized around the four overarching categories representing: (1) sources of uncertainty experienced in the classroom; (2) the teachers’ views of uncertainty as an inherent part of engineering; (3) pedagogical uncertainty, and (4) pedagogical approach to managing and leveraging student uncertainty. These three overarching categories illustrate uncertainty as it was revealed and interpreted throughout the course of a middle school engineering unit as it is integrated into a science classroom.

**Sources of uncertainty.** The sources of uncertainty that were experienced during the engineering unit are broken into sub-themes but, overall, were observed in relation to the complexity and unpredictability of the design task. These subthemes include: open-ended and divergent problem space, construction of physical artifacts, trade-offs required for optimization, and testing under real conditions with messy or unclear results. While the students experienced many elements of uncertainty, the teacher also faced some of the same uncertainties as the students. In conjunction with each of these sources of uncertainty, are the corresponding strategies or mindsets that were employed by the students, and at times the teacher, to deal with ambiguity and risk.
The unpredictable nature of an open-ended and divergent engineering challenge was observed in how the student and teacher expressed doubt of not knowing how a specific design would perform. Students, who were free to make their own design decisions, constantly questioned the teacher about their ideas, asking if their idea “would work” or how a specific feature might affect the performance. While Janice scaffolded the student at times with hints or questions to aid deeper thought or offer a new perspective on the issue, she often responded that she was unsure how a design or idea would perform. She would answer with responses like, “we’ll see” or “let’s try and see what happens.” While this uncertainty may have been a ploy for further engagement, she confirmed a genuine uncertainty at times by stating in a post lesson interview that she “wasn’t sure why they were doing that, but I let them try.” These interactions illustrate Janice’s comfort and honesty with uncertainty and promoted the mindset to try and see what happens, which appears to be tied to the affordance of the design process in allowing for failure and redesign.

The unpredictability of students’ designs was in part due to the complex and often uncertain nature of planning, designing and constructing a physical artifact. Due to the complexities and intricacies associated with constructing artifacts, the students, and at times the teacher, were observed feeling uncertain with how to construct certain design elements and how the construction technique might affect the design’s performance. For instance, the students struggled with decisions related to the intricacies of construction. The uncertainty was observed as the students questioned the effect of properly sealing or covering the window, how the glue might affect heat transfer, what effect insulating the floor might have, and needing to consider the “best” sequence for constructing their final design. The various intricacies, and ensuing questions, demonstrated the uncertainty students felt due to the complexity of dealing with new variables that arose as part of building physical prototypes. To help the students deal with these uncertainties, the teacher usually had a student-centered class discussion about how they should resolve these unanticipated issues.

In addition to the complexity associated with constructing artifacts, the students and teacher continuously discussed and debated design decisions in terms of the competing demands. These demands were discussed as constraints, such as time, cost, available materials and other trade-offs that must be weighed out in order to design the “best” house. These competing demands produce indecision throughout the project as Janice and her students debated the importance of aesthetics on whether the client would actually buy the house, evaluated economics in terms of initial high cost versus the long term benefit of keeping bills down, and weighed out the importance of minimizing temperature change versus cost. Throughout the process of optimization, the students and teacher, which in this case acted as the client, worked through these uncertainties by negotiating, prioritizing and ultimately making group level decisions about trade-offs.

Beyond the planning and construction, uncertainty was observed as it related to the inconsistency and imperfection of the testing conditions and resulting data. Due to testing the prototypes outside, the students and teacher questioned the reliability of these experimental conditions and accompanying results. For example, the class questioned the “fairness” of the results and discussed methods for establishing consistent testing procedures so results could be compared fairly. The class also faced variable and imperfect results due to testing outside. The students
identified wind, ground temperature, and angle of the sun as additional variables that needed to be considered in testing outside. This reveals that the authenticity of this task promoted critical thinking, monitoring, and reflective skills throughout the unit.

Further uncertainty arose as both the students and teacher were unable to definitely explain several results due to complexity and uniqueness of designs. The lack of a definitive answer left the class feeling irresolute about which aspect of the design was affecting the results. While the curriculum calls for groups to test one variable, students debated whether temperature increases were due to that specific design feature or other factors such as, the way it was sealed, if the window was covered, if air was trapped between layers of insulation, or the type of adhesive used. These unique and intricate design features challenged the conclusiveness of certain results and therefore the performance of the designs. The ambiguity related to this inconclusiveness as well as imperfect testing conditions fostered in-depth examination of the data, critical consideration of the cause of the results, and thorough justification through discussion and debate. However, this ambiguity also caused enough doubt that a few groups persisted in using unsuccessful design features. Much like the work of real engineers and scientists, the imperfect and inconsistent data forced Janice and her class to question the certainty of the results by reflecting, reasoning and making judgments about the causes for surprising behavior in the data.

Overall, these sources of uncertainty that students and teachers experience allow students to face and learn the skills necessary to deal with ambiguous and unpredictable situations. These findings show that several elements of the uncertainty inherent in engineering transferred into the classroom during an engineering design task.

**Janice’s interpretation of uncertainty.** In her comments, Janice talked about how students were engaging in engineering and described how dealing with uncertainty is part of what engineers do. During one lesson, Janice specifically stated to the students that being unsure about findings is “what engineers do.” She also explained in an interview that figuring out why something works or does not work is “what engineering is supposed to be.” These examples illustrate Janice’s explicit interpretation that uncertainty is an inherent aspect of engineering.

Beyond this recognition of uncertainty as part of engineering, Janice discussed the benefits and success of the unit in relation to learning to deal with uncertainty. An example came from her final interview when she was asked about the key benefits of the unit. Janice responded by describing how it was helping students develop into critical thinkers and problem solvers who were able to “deal with complex and uncertain open-ended problems.” She also stated that a major success of the unit came from the students demonstrating perseverance in how they would “try it, fail, figure it out” while dealing with the “complex process of engineering to find the ‘best’ solution for the client.” From these comments, Janice appears to acknowledge that dealing with uncertainty is an important skill for students to develop when learning to solve complex problems. Overall, Janice appears to interpret uncertainty as both an inherent aspect of engineering and a central aspect and benefit of engineering education.

**Pedagogical uncertainty of an engineering task.** In addition to Janice’s interpretation of uncertainty as an inherent aspect of engineering, Janice faces concerns and challenges related to
her pedagogical uncertainty. This uncertainty was associated with a limited knowledge base and task level elements of the engineering unit.

Janice’s knowledge based concerns begin before the unit even starts when she states in the pre-interview that she is concerned that she does “not know the material enough.” However, field observations showed Janice as having a competent understanding of the engineering design process and what engineers do. Her lack of knowledge was observed more in her understanding the three types of heat transfer at the level where she can support the students in separating and applying them to the designs. Janice seemed uncertain about how to scaffold and facilitate the students in these high cognitive level tasks. This uncertainty about the science content and how it should be integrated with engineering becomes evident as she faces a constant and continuous struggle to help the students with their confusion of separating heat into three types and applying this understanding to the designs. Throughout my field observations, the students seemed unsure of the difference between convection, conduction and radiation or how to test them separately in their designs. During the second part of the unit, the curriculum called for students to explore and apply the three types of heat transfer by starting with an inquiry-based experiment and then designing, testing, and applying each type of heat transfer separately. This is meant to help the students collect and compare data that will inform their final designs. An example of the confusion, which occurred numerous times over the course of the unit, took place when the students were instructed to focus solely on conduction by testing different types of insulation; however several groups poked holes on top of their insulation or tried to add vents in an attic space, both examples of convection. Correspondingly, when focusing on radiation, the teacher allowed students to use insulation materials in addition to different types of coverings, which were meant to block heat radiation. By confusing and mixing different types of heat transfer, the data collected becomes conflated with less definitive results. These examples illustrate the challenges and uncertainty Janice faced in understanding and helping the students who were mixing up and not fully understanding the different types of heat transfer, especially at a level where they could apply it.

To manage the pedagogical uncertainty of how to help the students understand and apply the different types of heat transfer, Janice tried out various strategies throughout the unit. These strategies included: (1) preparation in the form of spending out of class time to grasp the material herself and relying more heavily on curriculum materials; (2) informal assessment with individual white boards, and end of lesson reflections; (3) explicit explanation or direct instruction using videos and small review sessions during bellwork, which is a quick activity that begins as the students walk in; (4) emphasizing planning time that encouraged the application of science concepts instead of “just jumping in and try this and try that;” and (5) providing scaffolding by walking around to answer questions and provide guidance. While each of these strategies was successful in its own way, Janice continued to face the challenge of helping her students understand and apply the different types of heat transfer. One strategy, which was noticeably missing from the strategies, was the use of inquiry-based experiments to first explore the types of heat transfer. When asked about the absence of these experiments, Janice stated that she decided to rely more on video and explicit explanations of science concepts due to a lack of time and materials. This pedagogical uncertainty highlights the uncertainty teachers face while attempting to integrate the introduction of science concepts through inquiry and the application of this knowledge to design.
Field observation and interviews also illuminated task-based uncertainty in the form of what and when to emphasize particular aspects of this engineering design unit. In the pre-interview, Janice states that she is concerned about “Fitting this unit within her required curriculum and standards” and “keeping the kids engaged for four weeks.” These concerns translate into the uncertainty of how to prioritize time and effort within the constraints and responsibilities of a middle school science teacher. Similar to Janice’s struggle to find the “best” way to support students’ understanding and application of heat transfer, Janice faced uncertainty of when to introduce and how much emphasis to place on cost or measurement of materials. She first decided to introduce cost at the beginning so the students would keep it in mind during the designing and testing and as a way to minimize wastefulness of materials. However, this turned out to “stress the students out” and was later deemphasized until the final design phase. Another task level uncertainty arose with how to manage building time and student engagement. Some groups with more complex designs worked endlessly while other groups finished early. This forced Janice into a trial and error process of how to manage build time while keeping all groups engaged. Eventually, Janice chose to strictly enforce time limits and emphasize it as a constraint that all engineers must deal with. As Janice worked to allow each group to finish their design, managing time continued to be a major obstacle but one that Janice and the students learned to deal with and overcome, similar to a real world situation.

While Janice faced pedagogical uncertainties throughout the engineering unit, in the end she felt the unit “went well overall” and helped the students grasp the concepts of heat transfer. She described the overall success as strengthening skills in science, math, and problem solving. She also stated that it developed communication skills where students were “able to articulate their ideas, rethink answers, evaluate decisions and justify design.” Janice also reported a high level of interest and engagement from the students who would go to their next class and talk about the design, come in during lunch to talk about the project, stop her in the hall or out of class to ask questions or discuss a new idea.

Dealing with student uncertainty. This section describes the three subcategories that emerged in relation to the ways Janice encouraged and leveraged uncertainty during this engineering task. These subcategories include: (1) safe, student-centered approach; (2) using engineering design to face uncertainty; and (3) Discussion, Negotiation and Reflection.

Throughout the observations, Janice exhibited a calm attitude and gentle demeanor that established a safe collaborative environment where the majority of students were found to be on task, sharing ideas and working together to plan, build and test their designs. Within this safe learning environment, Janice took a pedagogical position that could be described as a student-centered, “Let them go and try” approach that promoted risk taking, autonomy, and control. By allowing groups to make their own design decisions and mistakes with minimal teacher input, Janice promoted the idea that it is okay to take risks in the face of uncertainty. Janice further promoted student ownership and accountability by letting the class come to a consensus about the ways to “fairly” test the designs and graph the data. For example, the class discussed and ultimately voted on whether to keep all boxes at the same angle relative to the sun and what scale and intervals should be used to collect and graph data. By allowing students this control and ownership, Janice released some of her own control without considerable risk to her intellectual
authority. It also enabled her to leverage uncertainty as a learning tool. This resulted in students learning to manage their own uncertainty by reasoning through some of the ambiguity related to design decisions, testing, and graphing.

In conjunction with her student-centered approach, Janice encouraged students to make mistakes and learn through a process of failure and redesign. She consistently expressed that it was “okay to fail” because “this is how you find out what worked and didn’t work.” By encouraging students to try, experience failure and figure out what happened, Janice and her students were able to cope with the unpredictable nature of engineering. Instead of fearing the uncertainty of not knowing how the design will perform, the students started to see it as a learning opportunity. In addition to helping students cope with uncertainty, Janice was able to cope with her own uncertainty of whether a student’s design would work. Janice expressed acceptance in her uncertainty during several post lesson interviews, stating in one interview that she “wasn’t sure why they were doing that, but let them try, let the kids figure it out.” These comments demonstrate how Janice shared the students’ uncertainty in not knowing the answer or how a design would perform. By accepting unpredictability and failure as important parts of engineering, Janice and her students were able to manage and leverage it as a learning opportunity. This acknowledgment and acceptance shows Janice’s perspective of uncertainty as an asset rather than a liability and links her affirmative perspective to the understanding that this is the way engineers deal with uncertainty.

The final pedagogical approach Janice utilized to manage and leverage uncertainty is associated with the social aspect of engineering and categorized as discussion, negotiation and reflection. Throughout the unit, Janice prompted group discussion, negotiation and reflection with questions like “what do you think worked well and why?” “what does your graph show?” or “why do you think your temp came back up?” In additional small group discussions, groups were required to present their design and test results to the whole class. At the conclusion of each presentation, each group took questions from the class. During these peer questioning sessions, or what could be considered peer assessment, the students asked challenging questions, noticed and discussed things the teacher did not think of, and seemed genuinely interested in the reasons behind each group’s design decisions and results. As a result of these presentations and peer questions, each group was forced to justify their decisions and interpretations as the class prepared to compare the results. Together they debated, negotiated and eventually reasoned through some of their uncertainty.

In summary, the way uncertainty transpired in the classroom paralleled the uncertainty faced by professional engineers. Uncertainty was observed as it related to the complexity and unpredictability of designing physical artifacts, managing the competing demands, optimizing the solution, and dealing with inconsistent and imperfect testing conditions and results. These elements of uncertainty transpired in part due to Janice’s recognition of uncertainty as an inherent and beneficial part of engineering. As a first time teacher of engineering, Janice faced challenges and concerns related to pedagogical and task based uncertainty, but she was able to work through these issues and found the engineering unit to be a success. Overall, Janice took the perspective of uncertainty as an asset. As a result of this perspective, Janice strove to incorporate, manage and even leverage the uncertainty by taking a student-centered approach.
that actively promoted autonomy, learning through a process of failure and redesign; and allowing for continuous discussion, negotiation and reflection.

Discussion

K-12 engineering education is still a new and emerging field with few empirical studies that have examined teachers’ experience and views of the uncertainty inherent in engineering. The results of this study, while limited to a single case study, provide valuable information for both researchers and teacher educators in the field of K-12 engineering education. Due to the small scale of this exploratory study, additional research is needed to confirm these results and further investigate how K-12 teachers interpret and manage uncertainty while teaching engineering.

Research has shown that engineering is filled with various elements of uncertainty and engineers must develop the skills and strategies to deal with uncertainty. The results of this study show that much of the same doubt, ambiguity, and unpredictability that the students faced matches what the literature describes as inherent parts of engineering. Furthermore, the sources of uncertainty, which were experienced by the students, provided opportunities to develop some of the same skills that engineers use to manage and reason through uncertainty. Therefore, this study endorses the premise that engineering design tasks support the development of high-level problem solving skills.

In exploring Janice’s experience and interpretations, this study adds to the literature by improving the field’s understanding of how teachers interpret, incorporate, and deal with the ambiguity and complexity inherent in the process of engineering design. Engineering appears to help teachers move away from productive efficacy that is perpetuated in school and provides means for learning the high level skills needed to solve ill-structured problems. Doyle and Carter found that students experienced a great deal of uncertainty related to the possibility of failure to meet evaluation criteria associated with an academic task. However, little evidence of student fear and/or uncertainty was observed. The lack of fear appears to be due to the way that accountability and risk of failure was minimized through the iterative quality of the design process. The design process also helped Janice welcome and minimize her own content knowledge uncertainty of not knowing if or how a design would perform. This allowed Janice to maintain a sense of authority because it was okay to be unsure, as it is part of engineering. Engineering, therefore, seems to reduce what Floden and Clark describe as a teacher’s content knowledge and authoritative uncertainty.

Similar to the finding of other researchers, Janice faced the challenge and accompanying uncertainty of how to successfully help students understand and apply science concepts to their designs. While the curriculum was designed to address this problem by breaking up heat transfer into three separate activities where the students could apply, test, and gather data to support their design decisions, Janice struggled to find a successful strategy or set of strategies to scaffold the students. This highlights what Floden and Clark describe as the pedagogical uncertainty teachers face when deciding how much to scaffold or let students struggle, how much time to spend on a topic, and which pedagogical strategies to use when integrating and infusing inquiry and application, all while working within the constraints of a middle school teacher’s time and responsibilities. While this confirms earlier research, it also adds by highlighting how this type
of pedagogical uncertainty plays out and is managed by a middle school science teacher who is attempting to integrate engineering into their classroom.

While most teachers tend to deal with uncertainty by reducing it, ignoring it and avoiding it altogether, Janice was instead able to welcome, acknowledge and leverage uncertainty during this engineering task. Janice’s willingness to sustain a certain level of doubt and uncertainty, enabled her to realize the benefits of uncertainty as an important skill for problem solving and something the students could handle. Helsing argues that teachers, who view uncertainty as a means for purposeful inquiry into their practice, welcome it as an asset or pedagogical tool that can strengthen teaching and learning. Janice, whose acceptance of uncertainty matches this mindset, was able to take certain risks and enter into a type of purposeful inquiry that gave her new insight into teaching and supported her growth as a teacher. O’Brien and his colleagues have shown engineering education to help teachers transform their instruction into a more project-based, hands-on and student-centered approach. This was evident in how Janice fostered a safe, student-centered learning environment that promoted autonomy and self-directed problem solving through student-led discussion, negotiation, reflection and decision-making. Doyle found that novel, high-level tasks with indirect instruction are exceptionally risky and ambiguous. What this study adds to the literature is how the engineering design process within a safe, student-centered learning environment appears to alleviate some of the risk and ambiguity. The understanding that engineers face uncertainty though the iterative design process appears to have supported both the teacher and students in facing and developing the skills to manage uncertainty. However, it is important to note that Janice was already a teacher with a more constructivist, student centered philosophy so she was willing to take some doubt and risk associated with uncertainty. Future research studies should examine how teachers of various teaching philosophies, such as behaviorist or constructivist, will be afforded from the engineering design process in allowing for uncertainty.

Overall, the findings show that a student-centered pedagogy, arranged around the iterative design process, can help teachers welcome and manage their own uncertainty, while also leveraging uncertainty to increase learning for their students. I am hopeful that the results of this study can be used to better prepare and support educators to teach engineering in a way that incorporates and leverages uncertainty in a manageable way. While this study provides new insight into uncertainty, much more research is needed. Future research questions include: Will teachers, who are resistant or unwilling to sustain a sense of doubt and uncertainty in their own practice, allow students to face uncertainty?; How do teachers use negotiation as a tool to promote and scaffold the uncertainty of an open-ended engineering design task?; What elements of engineering or an engineering task could help teachers welcome and embrace ambiguity and risk, and allow for students to face ambiguity?
References:

31. NGSS Lead States. (2013). *Next Generation Science Standards: For States, By States*. Achieve, Inc. on behalf of the twenty-six states and partners that collaborated on the NGSS.