IJEMST

International Journal of Education in Mathematics, Science and Technology

ISSN: 2147-611X

International Journal of Education in Mathematics, Science and Technology (IJEMST)

www.ijemst.com

Informed Designers? Students' Reflections on Their Engineering Design Process

Kerrie A. Douglas, Tamara J. Moore, Amanda C. Johnston, Hillary E. Merzdorf
Purdue University

To cite this article:

Douglas, K.A., Moore, T.J., Johnston, A.C., & Merzdorf, H.E. (2018). Informed designers? Students' reflections on their engineering design process. *International Journal of Education in Mathematics, Science and Technology (IJEMST), 6*(4), 443-459. DOI:10.18404/ijemst.440347

International Journal of Education in Mathematics, Science and Technology

Volume 6, Number 4, 2018 DOI:10.18404/ijemst.440347

Informed Designers? Students' Reflections on Their Engineering Design Process

Kerrie A. Douglas, Tamara J. Moore, Amanda C. Johnston, Hillary E. Merzdorf

Article Info

Article History

Received:
03 July 2017

Accepted:
11 November 2017

Keywords

Engineering
Assessment
Notebooks

Abstract

Assessment of students' critical thinking and problem solving in engineering is a real challenge for classroom teachers and researchers. Yet, students demonstrate evidence of learning through multiple means, including written reflections. The purpose of this study was to explore how students in grades 5 and 7 reflect on what they had learned about engineering design practices in comparison to their previous understandings. The researchers applied qualitative content analysis to analyze student responses to engineering notebook prompts that asked students to reflect on their understanding of the problem and how to design solutions. Data were collected from two classrooms (n = 47) that had implemented integrated STEM curricula. The results of this study indicate that students were able to reflect meaningfully on their engineering practices and how their understanding of what it meant to design had changed. The notebooks provided an opportunity for students to demonstrate evidence of their learning through reflection on their own design practices. The findings suggest that teachers and curriculum developers can use reflection as a means to help students connect their own learning to informed design practices, which may help students move toward being independent informed designers. Future research should consider how teachers can use notebooks to provide feedback on engineering practices.

Introduction

Recent reform efforts in science education call for integration of science, engineering, and mathematics to promote deeper levels of learning, including critical thinking, decision making, and problem solving based on content understanding (Australian Council of Learned Academies, 2013; NGSS Lead States, 2013). Development and implementation of the Next Generation Science Standards (NGSS Lead States, 2013) is one of the most significant of such efforts in the United States. STEM integration curricula support this disciplinary learning by engaging students in engineering design practices as a means to develop technologies through the integration and application of science and/or mathematics (Moore & Smith, 2014). STEM integration curricula provide promising opportunities for students to develop the critical thinking, problem solving, and decision making intended under the NGSS, because engineering challenges are by nature open-ended with many solution possibilities. Therefore, they add a layer of complexity to students' thinking and learning, requiring them to solve complex problems, think critically about their solutions and the evidence for their solutions, and make decisions based on this evidence. However, STEM integration and engineering challenges also add complexity to the assessment of student learning. Thus, methods of classroom assessment must enable teachers to assess student learning when there is not one "correct" solution and when solutions may not function as intended.

Many approaches to integrated STEM assessment at the precollege level have focused on memorization levels of learning—for example, understanding what the design process is and what engineers do, isolated from content understanding or context. Furthermore, there is a shortage of literature regarding classroom assessment of students' actual design practices. Requiring students to complete the stages of design does not ensure that students are meaningfully engaged in problem solving and critical thinking. For example, students tend to struggle with truly understanding the scope of the problem before jumping into solution generation (Atman et al., 2007; Atman, Cardella, Turns, & Adams, 2005). To successfully integrate engineering practices with science and mathematics concepts, there is a need to examine strategies within STEM integration to assess how students think critically, problem solve, and make decisions about their engineering designs based on their knowledge of engineering practices and science and mathematics concepts. This study explores the use of engineering notebooks to capture evidence of student reflections on their understanding of problem scoping and the engineering design process after completion of a STEM integration unit. Specifically, this study examines students' reflections on changes in their understanding of the specific design problem and changes in their understanding of how to develop a solution to a complex engineering design challenge, throughout the course of developing a solution.

Background

Engineering practices are behaviors that engineers engage in as they design solutions in a systematic way. Such practices begin with defining a problem and its criteria and constraints (NRC, 2012). With models, simulations, and representations, students formulate design ideas and conduct investigations to answer questions and collect data about a design from tests (NRC, 2012). Students interpret patterns in data to make inferences about design performance, using mathematical and computational thinking, and build arguments about their design with this evidence (NRC, 2012). These practices support the overarching engineering practice of constructing explanations and designing solutions (NRC, 2012). Through engagement with engineering practices, students are given the opportunity to interact with content in a way that promotes critical thinking, problem solving, and reflection (Moore et al., 2014). Rather than emphasizing low levels of understanding content (*e.g.*, memorized facts without real-world context), proficiency in science has been defined as expectations regarding what students know and are able to do (Pellegrino, 2012). Recent reforms in science, mathematics, and technology education aim to integrate these expectations into the classroom through integration of the subjects (NGSS Lead States, 2013). Engineering design challenges provide a context that frames the science, technology, and mathematics concepts and engineering practices. The Framework for K-12 Science Education (NRC, 2012) recommends that practices and content be integrated within curricula using performance expectations. Additionally, the STEM Road Map (Peters-Burton, Moore, & Johnson, 2016) provides guidelines to teach science and mathematics topics where engineering design practices are the integrator for the different content areas. Students must demonstrate their learning of science and mathematics through justification of their design decisions and the use of 21^{st} century skills.

Students demonstrate evidence of learning in multiple ways. As teachers attune to formative assessment based on everyday learning, they can obtain evidence to guide in-moment responses which help move students forward and guide their future instruction (Black & Wiliam, 1998). Formative assessment checks for understanding of manageable portions of learning using a low-stakes, high-frequency approach. Formative assessment strategies can be used to promote self-regulation and metacognition by increasing students' awareness of their own use of learning strategies (Black & Wiliam, 2009; Hudesman et al., 2013). For example, teachers can point out behaviors and performance under students' control they can modify to reach learning expectations (Gibbs & Simpson, 2004). Researchers have found that students' performance and self-efficacy improved when teacher advice linked self-regulatory strategies with course performance (Hudesman et al., 2013). In this way, students can develop new strategies and monitor subsequent outcomes, while moving toward greater proficiency (Clark, 2012; Wheatley, McInch, Fleming, & Lord, 2015). Engineering in the classroom allows for formative assessment by giving teachers evidence from authentic contexts, where students demonstrate their ability to use engineering practices, critical thinking, decision making, problem solving, and reflection about engineering.

Students' reflection, critical thinking, decision making, and problem solving in an engineering design are not readily measureable without a specific context where the skills are applied. Engineering notebooks are a resource for teachers to examine evidence of student performance and knowledge, because notebooks allow students to communicate skills that are not readily measurable in isolated tasks, such as using evidence to support their design decisions. As with engineers using notebooks throughout their projects, each student would maintain an engineering notebook to take notes, develop ideas, record testing and observations, and reflect on what they learned. Beyond simple documentation of work, notebooks can be used to familiarize students with the writing process of articulating thoughts through synthesis and interpretation (Rider-Bertrand, 2012). Keeping a notebook is an important practice in science and engineering wherein students collect sketches, calculations, and artifacts related to the design problem (Kelley, 2011). The habit of recording their ideas in notebooks requires students to synthesize their thoughts and record them in a concise manner that can be understood by others, particularly their teacher and teammates. In addition, students can use notebooks to formulate and defend their hypotheses with reflection and critical thinking (Fulton, 2017), because they have a place to keep track of their many and varied ideas throughout the process. Teachers can use notebooks to develop student-centered instructional practices by actively engaging all students in the process and having expectations for all students to record their ideas. Engaging with subjects at this depth also increases student ownership and personalization of learning (Marcarelli, 2010). Because they are embedded in the curriculum to provide first-hand evidence of interaction with the material, notebooks are conducive to being used as an assessment tool. Notebooks provide an opportunity for authentic assessment of engineering content and practices, and measure students' ability to perform design tasks as well as their conceptual learning.

Researchers have begun to consider engineering notebooks as an important part of STEM integration learning opportunities. Notebooks are particularly useful when embedded into the curriculum to support students through the design project (Berland, McKenna, & Peacock, 2012). Notebooks have been found to scaffold students in completion of design activities and promote students' understanding of engineering practices (Hertel, Cunningham, & Kelly, 2017). However, researchers have found that, although teachers use notebooks to support stages of design, they struggle to use notebooks to support reflection (Berland et al., 2012). Therefore, there is a need to examine how students reflect on their own understanding of the problem in response to notebook prompts, to understand better how notebooks can be used to support and assess students' reflection of their thinking.

Theoretical Framework

Beginning designers approach engineering challenges differently than informed designers, both in their activity in the engineering design process and how they approach the design process. We examine multiple aspects of engineering design using a framework of engineering design competencies (Douglas, Moore, & Adams, 2016) on the spectrum of beginning to informed designers within each of the phases of engineering design (Crismond & Adams, 2012). The Core Engineering Design Competencies (Douglas, Moore, & Adams, 2016) framework provides a system for analyzing what students are doing during the design process by laying out three overarching design competencies that engineers engage in throughout an engineering design project [more information about the competencies and their specific, measurable learning objectives can be found at https://purr.purdue.edu/publications/2203/1].

Informed engineering designers engage in evidence-based reasoning (EBR) throughout the design process in a variety of ways and levels of depth (Gainsburg, 2006). Informed designers need to back up their design decisions with evidence because "in engineering, reasoning and argument are essential for finding the best possible solution to a problem" (NRC, 2012, p. 52). Engineers use evidence to justify their decisions throughout the design process in a variety of formal and informal ways (Gainsburg, Fox, & Solan, 2016). Engineers support their arguments with evidence based on scientific and mathematical principles, the criteria and constraints of the problem, and other external factors that affect the design. To use evidence from scientific and mathematical principles effectively, engineers must have a deep understanding of these principles and be able to integrate them with their engineering design skills (Mathis, Siverling, Glancy, Guzey, & Moore, 2016). Justifying their ideas with evidence both formally and informally is an important skill for engineers to utilize throughout the design process (NRC, 2012). Beginning designers engage in EBR, often when they are prompted by a teacher, but the quality of that EBR may be very different than informed designers' EBR (Mathis, et al., 2016). EBR is a common thread throughout the design competencies. These competencies were designed to be the basis for the assessment of the STEM integration curricula and were a guide for the scaffolding of prompts in the students' notebooks.

The competencies describe what engineers do within design, namely, problem scoping, generating solution, and communicating design ideas. The three competencies are:

1. *Problem Scoping*: Define the problem from the perspective of stakeholders. Students generate and then refine the description of the problem based on new information. Students engage in problem scoping to define the problem and needs, and then identify the knowledge, criteria, and constraints required for a desirable solution.
2. *Generating Solution*: Use evidence to develop an optimal solution. Students develop possible solutions, evaluate solutions, implement, test, and optimize the solution.
3. *Communicating Design Ideas*: Communicate their design solution through use of EBR (p. 5).

During STEM integration units, students engage in the practices and content of engineering. Therefore, in addition to looking at the content and what students are doing, which the design competencies help to define, we also must consider the strategies that students are using during the engineering design process. The Informed Design Teaching and Learning Matrix (Crismond & Adams, 2012) describes nine strategies that designers use and explains how these strategies differ in beginning and informed designers. The nine design strategies include:

1. Understand the challenge, 2. Build knowledge, 3. Generate ideas, 4. Represent ideas, 5. Weigh options and make decisions, 6. Conduct experiments, 7. Troubleshoot, 8. Revise/Iterate, and 9. Reflect on process. Within each of these strategies, Crismond and Adams (2012) described the patterns in differences between beginning and informed designers.

Together, the two frameworks present a comprehensive description of design and allow us to analyze the range of differences between beginning and informed designers. This will allow us to address the students' perceptions of engineering problem solving with respect to habits and practices of informed engineering designers. Table 1 includes each of the competencies and strategies from the two frameworks and shows their alignment that will be addressed in this framework. Both frameworks are based around the engineering design process and the skills and practices students must be able to do to engage successfully in engineering design. Therefore, the two frameworks are aligned based on how they fit together and where they fall in the engineering design process.

Table 1 Engineering design competencies and design strategies

Engineering Design Competency (Douglas, Moore, & Adams, 2016)	Design Strategy (Crismond & Adams, 2012)
1-Problem Scoping: Students define the problem from the perspective of stakeholders. Students generate and then refine description of problem based on new information. Students engage in problem scoping.	Understand the Challenge Build Knowledge Generate Ideas
2-Generating Solution: Students use evidence to develop an optimal solution. Specifically: develop possible solutions, evaluate solutions, implement, test, and optimize the solution.	Weigh Options and Make Decisions Conduct Experiments Troubleshoot Revise/Iterate
3-Communicating Design Ideas: Students communicate their design solution through use of evidence-based reasoning	Represent Ideas Reflect on Process

The following sections describe how these frameworks fit together to form the theoretical framework for this study.

Informed Designing within the Engineering Design Competencies

When students are learning engineering, their abilities in both the practices and content of engineering vary, and they demonstrate different levels of ability within the spectrum of beginning to informed designers. To analyze these differences, we will look at the abilities of students on the spectrum of beginning to informed designers and how they align with each of the design competencies that articulate students' design skills. The following sections are divided into the three competencies of problem scoping, solution generation, and communication, and explain how they align with the strategies described in the Informed Design Teaching and Learning Matrix (Crismond & Adams, 2012).

Problem Scoping

The first design competency is "Students define the problem from the perspective of stakeholders. Students generate and then refine description of problem based on new information. Students engage in problem scoping (i.e., define the problem and needs, and then identify the knowledge, criteria, and constraints required for a desirable solution)" (Douglas, Moore, & Adams, 2016, p. 5). This competency aligns with the matrix dimensions of Understand the Challenge and Build Knowledge. Crismond and Adams (2012) identify that in understanding the challenge, beginning designers perceive design tasks as well-structured and believe there is a single correct answer. Beginners attempt to solve the challenge immediately, whereas informed designers are more willing to consider the problem (Crismond & Adams, 2012). In the Build Knowledge strategy, beginners often do not take the time to "do research on users, write product histories, and collect information" (p. 752). Experienced designers take the time and effort to learn about the problem before looking for the solution.

In comparison studies between student and expert designers, informed designers spent more time on the design compared to beginning designers (Atman et al., 2007; Dorst, 2011; Mentzer, Becker, & Sutton, 2015) This time difference was significantly affected because informed designers spent more time learning about the problem and requesting more information about the problem (Atman et al., 2007; Mentzer et al., 2015). The information gathered by beginning designers was most frequently about material costs and other solution-focused questions, while informed designers asked more often about problem-focused information. Additionally, Bogusch, Turns, & Atman (2000) found that informed designers considered a broader range of factors, including logistical and social issues.

Time spent on problem scoping and requested information are not the only factors that should be used to measure problem scoping skills (Watkins, Spencer, & Hammer, 2014). Experience with ill-structured problems which, unlike traditional well-structured problems in a classroom, have challenges such as multiple conflicting goals, multiple feasible solutions, and constraints outside of engineering (Jonassen, Strobel, & Lee, 2006), leads experienced designers to approach problems differently than beginning designers. For example, they must be experienced with many different problems and designs to be able to relate the current problem with others in their experiences and apply their knowledge to new situations (Cross, 1982; Dorst, 2011; Kolko, 2010). Informed designers are also better able to "pursue predominantly 'breadth-first' and top-down strategies, and are more willing to reject an early solution when it is discovered to be fundamentally flawed" (Cross, 1982, p. 27).

Generating Solution

The second design competency is "Students use evidence to develop an optimal solution. Specifically: develop possible solutions, evaluate solutions, implement, test, and optimize the solution" (Douglas, Moore, & Adams, 2016, p. 5). This competency aligns with the matrix dimensions of Generate Ideas, Weigh Options and Make Decisions, Conduct Experiments, Troubleshoot, and Revise/Iterate. For the strategy of generating ideas, beginning designers work with one or a few designs and are reluctant to change the idea, pay little attention to criteria and constraints, and do not consider benefits and tradeoffs. On the other hand, informed designers brainstorm multiple solutions and balance these multiple solutions with the benefits, tradeoffs, criteria, and constraints of the design space (Crismond & Adams, 2012).

For conducting tests and experiments, the few tests that beginners conduct do little to improve understanding, because they tend to change multiple variables simultaneously rather than testing specific features. Informed designers run valid tests to learn about the design (Crismond & Adams, 2012). For the troubleshooting strategy, beginners are unfocused and non-analytical, whereas informed designers "focus their attention on problematic areas of their potential solutions" (Crismond & Adams, 2012, p. 767). Finally, beginners revise in random ways as problems emerge or treat the iterations as a linear process. Informed designers "manage their time and resources strategically and use design strategies multiple times in any order, as needed, in a systematic way" (Crismond & Adams, 2012, p. 769) based on feedback.

The process of solution generation is often unique to each particular designer. In a phenomenographic study, Daly, Adams, and Bodner (2012) identified six categories that informed designers fall into: design as evidence-based decision-making, organized translation, personal synthesis, intentional progression, directed creative exploration, and freedom. The informed designers in this study comprised a wide range of specializations. However, even though there are differences in the specific methods and perceptions informed designers have of design, they have many common thought processes and skills. For example, informed designers use their ability to synthesize the information they have and to develop a solution using the methods of prioritizing, judging, and forging connections (Kolko, 2010). Unlike scientists and scholars who can "suspend their judgements and decision until more is known," designers are "constrained to produce a practicable result within a specific time limit" (Cross, 1982, p. 7), which causes designers to have different approaches to problem solving than scientists or scholars.

During solution generation, designers must balance multiple variables and considerations. The ability to do this efficiently is a major difference between beginning and informed designers. Informed designers are deliberate and efficient in their design strategies whereas novice designers are not as systematic (Dorst, 2011). For example, informed designers use their organization to gain a complete picture of the design space before drawing conclusions (Kolko, 2010). Informed designers take the time and use their skills to balance multiple ideas before drawing conclusions. Beginners struggle to see the range of possible solutions and balance these many solutions as they analyze them. Additionally, informed designers spend more time judging the feasibility of a solution and "they clarify constraints, criteria, and necessary functions of their solutions" (Mentzer et al., 2015, p. 429). Beginners tend to get fixated on one idea more often than informed designers (Cross, 1982). Mentzer and colleagues (2015) also found that students frequently fixated on one specific solution without consideration of alternatives. Beginning designers are less able to develop multiple solutions and to judge the feasibility of their solutions.

Communicating Design Ideas

The final design competency is: "Students communicate their design solution through use of evidence-based reasoning" (Douglas, Moore, & Adams, 2016, p. 5). This competency aligns with the matrix dimensions of Represent Ideas and Reflect on Process. Much of design happens internally, and designers need many skills to be able to express and communicate their ideas (Kolko, 2010). Communication is a key soft skill that engineers need for working effectively as engineering designers. (Acosta, Leon, Conrad, & Malave, 2010).

Informed designers use a wider variety of methods to communicate their ideas than beginning designers. Crismond and Adams (2012) found that informed designers used methods of communication such as "gestures, words, and artifacts … make drawings, construct physical prototypes, and create virtual models" (p. 758) to communicate viable solutions. However, beginners communicate their solutions through much more limited methods. Additionally, informed designers engage in reflective thinking throughout the design process, but beginners do not typically engage in reflection (Crismond & Adams, 2012). Reflection forces designers to keep tabs on their process and products throughout the design process. Additionally, informed designers use metacognitive strategies to monitor their thinking and think about how their thinking has changed during the design process as a way to monitor their process (Crismond & Adams, 2012; Flavell, 1979; Goos, 2002; Perrenet, Bouhuijs, & Smits, 2000). Together, reflection and metacognition are essential skills students need, not only to monitor their design, but also to develop deeper levels of understanding about their skills and to understand their knowledge of problem solving and engineering design (Daly, Adams, & Bodner, 2012; Goos, 2002).

Communication is often cited as an important skill for engineers. One of the ABET (ABET, 2013) student outcomes is "an ability to communicate effectively" (p. 3). One of the key skills identified by the National Academy of Engineering's "The Engineer of 2020" report (2004) that engineers of the future will need is good communication. The joint National Academy of Engineering [NAE] and National Research Council [NRC] report (2009) includes communication as an important engineering habit of mind that should be promoted in precollege engineering education because "communication is essential to effective collaboration, to understanding the particular wants and needs of a 'customer,' and to explaining and justifying the final design solution" (p. 5).This research study is concerned with students' reflections of their engineering problem solving activities and processes during participation in an engineering design-based STEM integration unit. The theoretical framework described above blends the two existing frameworks of the Engineering Design Competencies and the Informed Design Teaching and Learning Matrix to create a lens of what designers are doing and what strategies they are employing when participating in engineering design.

Methods

Students in our study participated in engineering design-based STEM integration units that required the use of engineering notebooks as a tool to capture engineering thinking, engineering design decisions, and understanding of the science and mathematics concepts that contribute to their design. To assess students' work in engineering notebooks, we looked at aspects of how they think about engineering design and what they were doing during the process. This study employs a naturalistic inquiry methodology (Lincoln & Guba, 1985; Patton, 2015) with a lens of *informed designing within the engineering design competencies* as described in the theoretical framework section. Our research question is, *What are the reflections of fifth- and seventh-grade students of their engineering problem solving processes after completing an engineering design-based STEM integration unit?* To answer our research question, we focused our study on the notebook responses of students from two classrooms (grades 5 and 7, ages 10-11 and 12-13) engaged in STEM integration curricular units from the EngrTEAMS project.

Project and Curricula

The EngrTEAMS project is a National Science Foundation-funded curriculum development and instructional coaching project. The project is aimed at researching and developing curricula for students in grades five through eight, ages 9 through 14. The curricular units implemented as part of this research initially were developed by teams of teachers through the first three iterations of a design research study and then redesigned using the research data from the teachers' implementations for the fourth iteration. Each curricular unit presents science content in the context of a unique, open-ended engineering design challenge mapped to Common Core State Standards for Mathematics (CCSSM) and Next Generation Science Standards (NGSS). The units are designed to be taught in science courses by science teachers and cover standards-based science content in the context of the engineering design challenge, with the goal that students learn both the science and engineering concepts. The fifth-grade unit focused on physical science content, specifically earthquakes and renewable energy, to design an anchor to support a wind turbine through earthquakes, and the seventh-grade unit focused on life science content, specifically ecosystems and biodiversity, to design a nesting platform to help loons overcome human encroachment. These two units and grade levels were chosen for our study to provide information from two different contexts and grade levels to get a broad picture of the grade band.

Although the units covered different content branches of science and engineering, the engineering design process in each was presented in the same way, with slight variations due to teacher differences. Similarities included a common engineering design process, the process of design (POD) which included the stages of define, learn, plan, try, test, and decide, and similar order of presentation of engineering concepts. Additionally, throughout each unit, students responded to common assessment items in engineering notebooks. The notebooks served as embedded assessment tools for all three of the engineering competencies. To do this, the notebooks included prompts that the students completed at various stages of the engineering design process. For example, each unit included problem scoping prompts, solution generation and selection prompts, and testing and evaluation prompts. These prompts were developed to provide formative assessment of students' work in the engineering design process and their abilities to bring in evidence for their decisions based on the science and mathematics they learned throughout the unit. Students also recorded work in their notebook for many of the mathematics and science concepts they learned in the unit.

Setting and Participants

The students of two teachers from the EngrTEAMS project participated in this study. At the time of data collection, both teachers taught in a second-ring suburban district in the midwestern United States with approximately 17,000 students in grades K-12. In this district, there were 25% students of color, and 19% of students receiving free or reduced-price lunch. The fifth-grade class included work from 19 students and the seventh-grade class included 28 students, for a total of 47 students included in this study.

Data Collection

The data collected for this study consisted of the completed notebooks for each student in each classroom. Each notebook contains approximately 26 pages of students' design work. Notebooks were collected, scanned, returned to the student, then de-identified for research purposes. The notebooks for both classes included common prompts for the two curricular units. For this study, we analyzed the responses to the end-of-unit reflection prompts that asked students to look back over their engineering notebooks to reflect on how their understanding changed over the course of the unit, thinking about the different aspects of the problem, including the science and mathematics that they spend many lessons learning. These prompts were the same in both units and were asked on the final day of the unit in both cases. Specifically, the notebook prompts stated:

> 1. Look back in your Engineering Notebook to see how you defined the problem throughout solving the problem. How has your understanding of the problem changed during the design process? Think in terms of client needs, criteria, constraints, and the science and mathematics needed to solve the problem.
>
> 2. Look back in your Engineering Notebook to see how you developed your solution throughout solving the problem. How has your understanding of how to design a solution changed during the design process? Think in terms of what you did and how you made decisions to solve the problem.

Data Analysis

We applied qualitative content analysis (Krippendorff, 2013; Schreier, 2012) to analyze the student responses to these notebook prompts. First, two researchers conducted open coding for the responses to the two prompts and developed independent codes. These codes were then compared, combined, and defined. Table 2 provides a list of agreed-upon codes generated after open coding along with a brief description of each.

Table 2. Codes and descriptions

Code	Description
Criteria/Constraints/ Context	Students identified that they learned about the criteria and constraints and the context (client and end user issues) which helped situate the way in which they would think about solutions.
Client or End Users	Students identified that they need to understand the needs of the client or end users.
Decisions	Students recognized that they made decisions.
Don't Understand	Students identified that they still do not understand the problem.
Iterative	Students see how iteration improves the design process by helping them arrive at a better end design solution.
Learned Science	Students identified that they learned something about the science content of the unit.
Learned from the Unit	Students identified activities and aspects of the unit that helped their understanding.
Multiple Ideas	Students identified the need for multiple solutions and recognize that not all of them will work.
Need Background Learning	Students recognized the need for background learning (particularly of the science concepts) to help them understand the problem space, which leads to better ability to design.
Need Data	Students recognized that they need data and sometimes further research to make their design decisions.
Need Tests	Students identified that they need to test their design. Use test results to evaluate and modify the design.
POD	Students recognized the need for the process of design (POD).
Solve Problem	Students identified that they needed to solve the problem or that they solved the problem. Students demonstrated that they have a basic understanding of the need to solve a problem.
Team	Students identified that they learned from their team.
Underdeveloped Early	Students realized that over the course of the design project, their understanding of the problem space was underdeveloped early and moved to a more sophisticated way of thinking.
Underestimate Complexity	Students identified that they underestimated the complexity of the problem or that they otherwise misunderstood the complexity.

The codes from Table 2 were then used for a second round of a priori coding. In the second round of coding, the two researchers coded to consensus for each student response using the software program NVivo. All of the student responses were coded with at least one code. During this process, codes were added and revised based on differences in student responses. If a student's response had aspects that fell within multiple codes, we coded it multiple times. After coding, all researchers worked together to group codes to form themes. The themes formed around related codes that demonstrated similar types of student thinking. These themes and examples within each theme are described in the results and discussion section.

Results and Discussion

The student reflections encompass a wide range of responses in terms of understanding, completeness, and content matter. Different students chose to reflect on different aspects of the unit and engineering design process. The responses fell into 16 distinct codes, which were organized into five major themes. The first theme was *Learned the depth of the problem and problem requirements* and included the codes Criteria/Constraints/Context and Underestimate Complexity. The second theme was *Learned science* and included the codes Learned Science and Client or End Users. The third theme was *Learned importance of testing and iteration* and included the codes Testing, Iteration, Multiple Ideas, and Need Data. The fourth theme was *Learned engineering design/problem solving* and included the codes Underdeveloped Early, POD, and Learned from Unit. The fifth theme was *Restated the engineering problem* and included the codes Don't Understand and Solve Problem. Responses presented here represent the breadth of student reflection, and although not all student responses are included there are representative responses for each code and theme. Additionally, although the students were asked two separate questions, their responses were often a crossover of the two questions and therefore all responses were grouped together in the analysis and results.

Learned the Depth of the Problem and Problem Requirements

The theme *Learned the Depth of the Problem and Problem Requirements* illustrates that students realized engineering design problems are not well-defined, but rather ill-defined, and therefore time and energy must be put into understanding the problem in depth. It includes the codes Criteria/Constraints/Context and Underestimate Complexity, and falls within the Engineering Design Competency of Problem Scoping and the strategy of Understanding the Challenge.

First, students identified that they learned what criteria and constraints were from the unit when they had previously not considered them. For example, one student admitted, "I had no clue at the beginning on what I would do, I didn't really think about the constants [constraints]." They learned how criteria and constraints served to define the problem, the expectations to be met, and the relative importance of some requirements over others. One student described how "the problem has changed for me like the constraints changed in ways. The budget was not important as much but we focused on the E. I. [environmental impact] more." At the end of the unit, students recognized that criteria and constraints increased their depth of understanding about the problem compared to the beginning. One student began the unit thinking "that loons just need a nest. Now, I believe our platform will protect the loons, give them shelter, and give them a place away from predators." Another student affirmed that "I now know how much it [the loon nesting platform] has to hold. I know that babys [sic] need an easy way to access and they need privacy." The students indicated that criteria and constraints gave them a means of articulating the knowledge they acquired about the problem and evaluating the fit of their solution.

Second, by overlooking criteria and constraints, students also had underestimated the complexity of the design problem. In one way, they were surprised by the difficulty of solving a design problem; as a student said, "I thought that the problem would be easier to solve than it actually was." They also reflected that they did not fully grasp the level of involvement that would be expected of them; as one student indicated, "At first I thought we were going to just make a flat platform just as easy as that but then we started to learn about loons and what they needed and didn't like and I realized there was a lot more to it." However, students concluded that a more complex problem with detailed requirements ultimately would result in the production of a better design. One student said, "Before this, I thought that it'd be easy. Just to throw up some cardboard and done [sic]. Now I learned that it helps to learn about loons, and the habitat they live in. Also, it makes you think about a loon's life." Some students perceived that having a better knowledge of the problem complexity, in addition to an awareness of criteria and constraints, gave them a deeper understanding of the problem and its requirements.

This theme provided evidence that some students' perceptions of problem scoping changed over the course of the design project. Students indicated that they obtained a better understanding of the engineering challenge and its requirements. Some students demonstrated understanding that the challenge was not as simple as they initially thought, due to meeting multiple criteria and constraints related to the context and the end users. Some also indicated that they had misconceptions about what activities the unit would expect them to do, but that this changed over time. However, by the end of the unit they recognized that the design challenge required complex thinking and learning they had not previously expected.

Learned Science

The theme *Learned Science* provides evidence that students recognized that the science concepts were related to the engineering design challenge, and in particular that science can relate to end users' needs. It includes the codes Learned Science and Client or End Users, and falls within Engineering Design Competency of Problem Scoping and the strategy of Build Knowledge.

For some of the responses within this theme, students identified that they learned science over the course of the unit and identified specific topics they learned about. For example, a student wrote, "We have learned more about what loons do and their ecosystem that they live in." Another student wrote, "We learned about earthquakes and that changed my understanding." A third said that he "found out size & weight of loons also all facts about loons. What they do & don't like." These students thought about what they learned in the unit and were able to articulate that in their notebooks.

Other responses within this theme suggest that students saw the science as a way to understand the end user of the design. All of the responses from the loons unit that fell into this theme were related to learning about the loons and how they live. This fits with the context of the unit because the unit was largely focused on learning about the ecosystem of the loons. One student went even further in thinking about loons to say, "I felt empathy for the loons and started to see the loon perspective on the problem." This student's response provides evidence that the student is going beyond simply learning facts about a loon to seeing the end user's perspective of the problem and considering what the end user will need in the engineering design.

Within this theme, two important ideas were brought up by students. First, some students indicated that they learned science concepts throughout the challenge and that it changed how they viewed the problem. Second, specifically with the loons unit in which the loon was the end user of the design, students indicated that their viewpoint on loons' needs and the importance of those needs to their design changed over time.

Learned Importance of Testing and Iteration

The theme *Learned Importance of Testing and Iteration* represents how students understood the iterative process of conducting tests to evaluate a design. Data from tests are analyzed to determine the performance of the design, and multiple tests help to refine the design and arrive at a solution. This theme includes the codes Testing, Need Data, Iteration, and Multiple Ideas, and falls within the Engineering Design Competency of Generating Solution and the strategies of Generate Ideas, Weigh Options and Make Decisions, Conduct Experiments, Troubleshoot, and Revise/Iterate.

First, students identified the need to test their design and that the process of testing helped them learn about their design. For example, one student said, "After all of the trying and testing, we now know what works and what doesn't;" while another stated, "We changed designs because we wanted to see if it worked better but it did not work!!" These students identified that they carried out tests, and that the results of their tests let them know if their design worked or not. They did not discuss any specific aspects of their tests; however, they noticed that trying and testing helped them see both the positive and negative aspects of their designs.

Second, a few students started to realize that they needed to run tests and use the data when making their decisions. For example, one student said, "At first I didn't know how we would pick a lake, but now, we looked at data to pick it." Although this student does not discuss the specifics of the data or how they were used to pick the lake, the student identified that data were needed and helped to do something they could not do before.

Third, some students also concluded that after testing, they needed to change their design in an iterative process. For example, a student stated, "Well it failed so we came up with a new design and it's better." This student identified that since the test failed they needed to come up with a new design, which in turn was tested to show that it was better. Another example of a student more explicitly discussing iterations is, "You need to try more than once to actually learn something." These students recognized that engineering design is not a linear process to be completed once without iteration. They discussed trying more than once and having to restart to learn or to produce a design.

Finally, several students recognized the need for multiple ideas before they decided on a final solution. Some of the students in the examples above approached the idea of multiple solutions by stating that they used more than one idea in their process. Another student stated, "We changed the design many times and we finally did one that worked suuuuuuuuuper good [sic]!!" This student recognized that, to finally get their "super good" design, they needed to have several designs, and that their selected idea was not static but changed many times.

This theme supported the conclusion that some students perceived importance in developing different ideas and testing them out in iterations. Some students identified that they needed to test their design and to use the test results for evaluating and modifying their design. Other students recognized that they needed data and sometimes further research to make their design decisions. Students identified the need for multiple solutions and realized that not all of their ideas will work. Overall, students indicated that they saw how iteration improves the design process by helping them arrive at a better end design solution.

Learned Engineering Design/Problem Solving

The theme *Learned Engineering Design/Problem Solving* provides evidence that students believe their understanding of how to solve a difficult problem changed over the course of the unit. The student responses in this theme demonstrate that they have a better understanding of how to understand and develop a solution for a complex engineering problem and specifically reference processes that were introduced through the unit, including POD. This theme includes the codes Underdeveloped Early Understanding, Learned from the Unit, and POD, and has components that fall under all three Engineering Design Competencies because students are describing their overall understanding.

When asked how their understanding changed throughout the unit, many students identified that they did not understand the problem at the beginning of the unit. For example, a student stated, "My understanding has changed by finding out what did & didn't work & I had no clue at the beginning on what I would do [sic]," and another student said, "I didn't get it at all in the beginning and now I know how to fix that problem." Another stated, "My understanding was not very clear when we first started this engineering challenge. Now I get everything I needed to know in order to successfully build my platform." These students thought metacognitively about their ideas at the beginning of the unit and recognized that they did not have a good understanding of the problem. Their thinking went beyond reflection of what they had done towards thinking about their own thinking and how it changed throughout the process. However, they did not explain specific differences in their current understanding or what caused their understanding to change.

Other students identified specific things they learned from the unit. They went into more depth about their lack of understanding and explained what led to changes in their understanding. For example, three different students stated:

- "At the beginning I hardly even knew what the 'DNR' meant about a platform let alone build one. I was confused on what loons like or what materials we were going to use. But we did a lot of activities to help us understand how we were going to build it. When the day came of the loon building I was ready."
- "I didn't understand what we had to do, by like building our platform, but now after building and answering questions, I slowly started to understand more. And I didn't know much about loons before, but now I know more."
- "Well at first I wasn't really aware of the problem so I knew I had a lot to learn. When we did that one exercise with the white board markers really changed how I saw the problem. I felt empathy for the loons and started to see the loon perspective on the problem. After weeks I got into the assignment, learned more from friends and teachers and in conclusion fully understood the problem."

These students cited particular tasks in the unit that helped change their understanding, such as answering questions and doing the white board markers activity. They also identified particular aspects of knowledge they did not have, such as "what loons like." They thought not only about how their understanding changed, but also about what caused their understanding to change.

Some students identified that they perceive engineering design as a process and that they learned more about how to solve problems. For example, two other students said, "I didn't know how to design an anchor but now I know you have to plan, try, test and decide," and "I didn't know too much on how to come up with a solution for something like this, but after I learned more about loons & their homes, I started to figure out how to problem solve slowly." Other students identified that they believe their learning went beyond just their understanding of the specific problem they were working on, and included the broader concepts of problem solving and engineering design, such as one student who said, "I used to think you would think of something to make, build a prototype, then build the real thing is how you did it. Now I realize you have to use the POD and you might have to restart”. These students recognized that they learned about problem solving and the engineering design process. They cited specific phases of the design process that they used and reflected on how they have grown as problem solvers and designers in the context of the particular problems they worked on.

In this theme, students recognized their inability to solve the problem and that they needed supports and a process to solve it. One of the supports they identified is the POD. Many students perceive that over the course of the design project their understanding of the problem space was underdeveloped early and moved to a more sophisticated way of thinking. Some students identified activities and aspects of the unit that helped their understanding, while other students recognized the need for the design process and explained their new understanding of how to problem solve.

Restated the Engineering Problem

The theme *Restated the Engineering Problem* includes student responses to the questions that were incomplete or superficial responses and did not address changes in their understandings or perceptions. It includes the codes Don’t Understand and Solve Problem and encompasses all three Engineering Design Competencies, because students struggle to communicate their ideas about Problem Scoping and Generating Solutions. A few students did not understand or address the questions that were asked and instead described the problem that they were working on. There were several students who restated a broad description of the problem without reflecting on how their understanding changed throughout the unit. For example, in response to the first prompt about how their understanding of the problem changed, several students simply restated the problem, including one student who said “that you had to make a floating platform” and another said “picking a lake the fish and water clear.” These students are describing pieces of the problem they were working to solve, but did not articulate a complete understanding of either the problem or changes in their understanding.

Another student restated the problem more thoroughly by stating “Loons are precious to MN and are becoming very endangered so finding a lake & place (platform) is necessary. (and we did it).” This student recognized that this is the problem they worked to solve, but did not describe any changes in their understanding of the problem throughout the process of the unit. Additionally, this student stated that they solved the problem that they set out to do. Some students went into slightly more depth, but still lacked detail about their reflections on their understanding. For example, one student stated, “It [my understanding] has changed because I’ve learned more and I am more aware of what they need.” This student is answering the question that was asked without explaining how or what was learned. Other students simply stated that they had learned without going into detail about what that learning was or how they achieved the learning. For example, two different students said, “We learned more about the problem” and “I have a better understanding of the problem at hand.” These students are claiming that their understanding of the problem changed, but are not describing how it changed or what changed about their understanding. For the second question, “How has your understanding of how to design a solution changed during the design process?,” these same two students said, “We came up with a new design” and “We made very good decisions on how to solve the anchor,” respectively. Once again, these students recognized that they did something, a new design or made decisions, but they are not describing how their understanding changed or what changed about their understanding. This theme demonstrated that not all students reflected deeply on the unit. Some students superficially addressed the prompts without reflecting on how their understanding changed or what changed in their understanding because of the unit.

Synthesis

Our theoretical framework laid out many of the differences between beginning and informed designers. While this study was based on students’ reflection of their own learning, rather than performance assessment, the reflections demonstrate students’ engagement in the complex learning process of design and a glimpse into the variation between students in terms of becoming more informed designers. The purpose of this section is to analyze how students’ responses demonstrated variations in how they made design decisions based on information and in comparison to the literature on beginning and informed designers.

Perceptions of the Structure of Design Problems

A major difference between the design approaches of beginning and informed designers is their perception of the structure of the design challenge. Beginning designers perceive design tasks as well-structured (Crismond &

Adams, 2012, p. 747), whereas experienced designers are better able to recognize the ill-structured nature of design problems (Jonassen et al., 2006). This is especially a factor in classroom problem solving and design because students are accustomed to well-structured problems (Jonassen et al., 2006). Many students in this study were able to reflect on the complexity of the engineering design problem they worked on. Many indicated that they recognized flaws in their original thinking about the complexity of the problem and how they had underestimated this complexity. This was demonstrated in the themes *Learned engineering design/problem solving* and *Learned the depth of the problem and problem requirements* with many students stating a variation of "I had no clue at the beginning of what I would do" and how they came to understand better over the course of the design process. These students were able to identify that the problem was not well-structured, as they had originally thought, and needed different skills than they had anticipated. The students identified a variety of factors that helped them to learn more about the problem and its complexity, including testing failures, specific activities in the lessons, learning about and feeling empathy for the loons, and working with their teammates.

Because they view design tasks as ill-structured, informed designers take time to ask questions and learn more about the problem, including its criteria and constraints (Dorst, 2011; Dym, Agogino, Eris, Frey, & Leifer, 2005; Atman et al., 2007). A few students in the *Learned the depth of the problem and problem requirements* theme indicated that they learned more about what constraints were and what the constraints of the problem were. More often, as described in the previous paragraph, students indicated that they had underestimated the complexity of the problem rather than specific constraints or criteria they had not anticipated. This is an indication that they are recognizing the complexities involved with design problems and the challenges of an ill-structured problem, even though they might not be comfortable enough with the language to describe their thinking or be able to anticipate the types of questions they should ask in the same way as experienced engineers.

Importance of Multiple Solutions

Along with their misunderstandings of the complexity of engineering design problems, beginning designers often believe there is a single correct answer (Crismond & Adams, 2012) whereas informed designers recognize the need to develop multiple ideas and to avoid becoming fixated on a single initial idea (Cross, 1982). In their reflections, students recognized that their first idea did not always work, often citing that the testing process helped them to realize this, as demonstrated in the *Learned importance of testing and iteration* theme. Many students indicated that they needed to test multiple solutions before theirs finally worked. The realization that their idea did not work and that they needed to try a different one is a step towards being able to recognize the need for development of multiple possible ideas, which is often a difficult skill for students to learn (Welch, 1998; Welch, Barlex, & Lim, 2000) and a difficult skill to practice and teach effectively in the classroom (McCormick, Murphy, & Davidson, 1994). When developing multiple solutions, informed designers use the ability to balance multiple solution ideas (Crismond & Adams, 2012). The students who indicated that they had multiple ideas most often stated that they tried a new idea after initial ones had failed, rather than balancing multiple ideas at one time. However, along with their underestimation of the complexity of the problem, students were starting to realize the need for multiple solutions. Perhaps this could help to motivate them initially to develop those multiple ideas in future projects, and give them a reason to develop the skills involved with balancing multiple solutions.

Although students demonstrated their understanding of the need for multiple ideas, students did not discuss the process they used to develop their ideas. This is a likely a product of the phrasing of the questions students were asked, but is likely also a product of the thinking and design skills involved in conveying design ideas (Kolko, 2010). The skill of communicating their ideas and their ideation process is the underlying aspect of the Communicate Ideas competency. The process of developing an idea and explaining that development varies greatly among designers (Daly et al., 2012) and requires design experience to develop (Cross, 1982), making it a large step for the beginning designers in this study. Brainstorming is an important practice of informed designers to develop multiple ideas (Crismond & Adams, 2012; Dorst, 2011), which was absent in the student reflections. This might indicate that they did not thoroughly brainstorm or that they did not recognize the importance of brainstorming in the development of their solution. However, like the skill of explaining the development of their ideas, representing brainstorming requires high levels of cognitive and representational skills from the beginning designers in this study.

Design Skills

The skills of balancing multiple solutions, communicating ideas, and brainstorming are challenging and take practice with design to become proficient (Watkins et al., 2014). Therefore, it is not surprising that students do not demonstrate proficiency with these skills after only one relatively short engineering design unit. Although ideally "by the time students reach middle school they should have had numerous experiences in engineering design" (NGSS Lead States, 2013, p. 53), in reality students' experiences with design vary within the classroom. However, despite referencing only a single design experience, several students reflected broadly on how their new design skills have changed their ways of thinking about design, including the importance of iteration and testing, following the POD, and understanding the perspective of the end user. Several other students gave specifics about what they learned in this particular unit without reflecting on how their developing skills would help them in other design challenges, especially in the *Restated the engineering problem* theme. They demonstrated that, at a minimum, they recognized their accomplishment in better understanding of a difficult problem.

Informed designers "manage their time and resources strategically and use design strategies multiple times in any order, as needed, in a systematic way" (Crismond & Adams, 2012, p. 769) based on feedback. Several students, included in the *Learned importance of testing and iteration* and *Learned engineering design/problem solving* themes, recognized that the design process is not linear and they "might have to restart." They recognized the iterative nature of the design process that requires testing and changes to the design. Recognizing the iterative nature of engineering design is an important skill of informed designers and a key difference between beginning and informed designers (Dorst, 2011). A few of the students cited the phases of the engineering design process that they had practiced in the unit. These few students indicated that using a process helped to improve their design. However, more often, the students indicated that they had used the test results to see if their design worked without going into depth about how the test results changed their ideas about the design. Although they have not yet reached the level of effectively using iteration, they are developing ideas about testing and how to effectively use test results, which is a beginning of an iterative process.

Considerations of Time and User Needs

Informed designers spend more time on problem scoping than beginning designers (Atman et al., 2007; Mentzer et al., 2015). Although the nature and layout of the curriculum forced the students to spend certain amounts of time on each of the activities and phases of design, several students recognized the benefits of the time they spent and indicated that they needed to spend time on problem scoping. This was demonstrated in the themes *Learned engineering design/problem solving* and *Learned importance of testing and iteration*. Students recognized that learning and doing design takes time. They "slowly started to understand more" and needed the time to "fully understand the problem." The common idea that "at first I wasn't really aware of the problem" but now, after the learning in the unit, "fully understood the problem" indicates that students recognized the benefits of taking the time to learn about the problem, background, and engineering design skills.

Informed designers take the time to learn about the end user's needs (Crismond & Adams, 2012). In the seventh-grade life science-focused unit, several students reflected that they had learned more about the problem by seeing "the loons' perspective of the problem." This indicates that students are thinking about the needs of stakeholders and using information about the stakeholders' needs to improve their understanding of the problem and development of the solution. This was especially the case in the seventh-grade unit because the science content was directly related to the end users (the loons). These results were seen in the *Learned science* theme. Informed designers synthesize information to use evidence to make decisions about their design (Gainsburg et al., 2016; Douglas, Moore, & Adams, 2016; NRC, 2012). The evidence included by students in their explanations varied across the responses. Some students were able to use evidence ranging from citing examples of aspects of the curriculum that helped changed their understanding to citing specific examples of what they did and how they did it. Other students did not include evidence in their responses, and simply stated their thoughts without any other explanation.

Reflection and Metacognition

The students were asked to reflect on their work and many of the responses indicated that the students were reflecting on what they had done. Additionally, for several of the students, the questions prompted them to think about their thinking and their responses included details of their metacognition. This could be a product of the format of the prompts and student habits of responding to teacher questions. However, it could also indicate that the prompts presented a metacognitive "red flag" (Goos, 2002) that prompted them to think metacognitively. For example, many students stated that they used to think one thing, but now thing something else or that they did not understand the problem at the beginning or identified that they know more now than they used to, especially in the *Learned the depth of the problem and problem requirements* and the *Learned engineering design/problem solving* themes.

Conclusion

In this study, we found that fifth- and seventh-grade students were able to reflect meaningfully on their engineering design learning when they engaged in an engineering design-based STEM integration unit, and were provided with scaffolding for the engineering design process as well as in their reflections. The students were able to perceive initial weaknesses in their thinking and identify their growth in many aspects of engineering design. They were able to identify key components of engineering design, such as the need for testing and multiple ideas, and relate these to the specific example they worked through. Some students were able to anticipate how this might influence their future thinking. The notebooks provided an opportunity for students to reflect on their learning and their thinking about engineering design and problem solving.

Recommendations

This study has implications for how curricula and teachers present engineering design problems and their assessment. The scaffolded notebooks supported meaningful documentation of informed design and purposeful student reflection, aspects that have been difficult to assess in past engineering notebook studies (Berland et al., 2012; Hertel et al., 2017). We found evidence that the scaffolding provided in the engineering notebooks, both in their culminating reflections included in this paper as well as in the records from the rest of the notebooks, provided a structured opportunity for students to make connections about how their thinking changed. Students were able physically to look back at how they defined the problem at the beginning of the unit and reflect on how their understanding deepened. While a solution may have seemed relatively easy at first, after engaging in a STEM integration unit students were able to communicate a deeper understanding of design practices. This implies that teachers can utilize engineering notebooks in a variety of engineering design problem contexts to help students develop engineering problem solving skills in communication, reflection, problem scoping, and overall engineering design. Students also provided evidence of what they had learned and how their understandings of engineering practices changed, demonstrating the potential for teachers to use scaffolded notebooks as a means for assessing the higher-order levels of learning intended under NGSS. Future research should focus on how to use scaffolded notebooks as a tool for classroom assessment.

Acknowledgments

This work was made possible by a grant from the National Science Foundation (DRL-1238140). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

ABET. (2013). Criteria for accrediting engineering programs 2014-2015. *Cycle*, 25. Retrieved from http://www.abet.org/Linked Documents-UPDATE/Criteria and PP/C001 08-09 CAC Criteria 11-8-07.pdf

Acosta, C., Leon, J. V., Conrad, C., & Malave, C. O. (2010). *Global engineering: Design, decision making, and communication*. Boca Raton, FL: CRC Press. Australian Council of Learned Academies (2013). STEM: Country comparisons: International comparisons of science, technology, engineering and mathematics (STEM) education. Melbourne: ACOLA

Atman, C. J., Adams, R. S., Cardella, M. E., Turns, J., Mosborg, S., & Saleem, J. (2007). Engineering design processes: A comparison of students and expert practitioners. *Journal of Engineering Education*, *96*(4), 359–379. http://doi.org/10.1002/j.2168-9830.2007.tb00945.x

Atman, C. J., Cardella, M. E., Turns, J., & Adams, R. (2005). Comparing freshman and senior engineering design processes: An in-depth follow-up study. *Design Studies, 26*(4), 325-357. http://dx.doi.org/10.1016/j.destud.2004.0 9.005

Berland, L., McKenna, W., & Peacock, S. B. (2012). Understanding students' perceptions on the utility of engineering notebooks. *Advances in Engineering Education*, *3*(2), n2.

Black, P., & Wiliam, D. (1998). Assessment and classroom learning. *Assessment in Education: principles, policy & practice*, *5*(1), 7-74. http://dx.doi.org/10.1080/0969595980050102

Bogusch, L. L., Turns, J., & Atman, C. J. (2000). Engineering design factors: How broadly do students define problems? In *Proceedings of the Frontiers in Education Conference* (Vol. 2, pp. 7–12). http://doi.org/10.1109/FIE.2000.896664

Clark, I. (2012). Formative assessment: Assessment is for self-regulated learning. *Educational Psychology Review*, *24*(2), 205-249. http://doi.org/doi:10.1007/s10648-011-9191-6

Crismond, D. P., & Adams, R. S. (2012). The informed design teaching and learning matrix. *Journal of Engineering Education, 101*(4), 738–797. http://doi.org/10.1002/j.2168-9830.2012.tb01127.x

Cross, N. (1982). Designerly ways of knowing. In *Design Studies* (pp. 221–227). London: Springer.

Daly, S. R., Adams, R. S., & Bodner, G. M. (2012). What does it mean to design? A qualitative investigation of design professionals' experiences. *Journal of Engineering Education*, *101*(2), 187–219. http://doi.org/10.1002/j.2168-9830.2012.tb00048.x

Dorst, K. (2011). The core of "design thinking" and its application. *Design Studies*, *32*(6), 521–532. http://doi.org/10.1016/j.destud.2011.07.006

Douglas, K. A., Moore, T. J., & Adams, R. S. (2016). Core engineering design competencies for intermediate and middle grades. Purdue University Research Foundation. http://doi.org/10.4231/R7B56GQZ

Dym, C. L., Agogino, A. M., Eris, O., Frey, D., & Leifer, L. J. (2005). Engineering design thinking, teaching, and learning. *Journal of Engineering Education*, *20*(1), 103–120. http://doi.org/10.1109/EMR.2006.1679078

Flavell, J. H. (1979). Metacognition and cognitive monitoring: A new area of cognitive-developmental inquiry. *American Psychologist, 34*(10), 906-911. doi: 10.1037/0003-066X.34.10.906

Fulton, L. (2017). Science notebooks as learning tools. *Science and Children*, *54*(6), 80. https://doi.org/10.1016/S0191-491X(04)90004-1

Gainsburg, J. (2006). The mathematical disposition of structural engineers. *Mathematical Thinking and Learning*, *8*(1), 3–36. http://doi.org/10.1207/s15327833mtl0801

Gainsburg, J., Fox, J., & Solan, L. M. (2016). Argumentation and decision making in professional practice. *Theory Into Practice*, *55*(4), 332–341. http://doi.org/10.1080/00405841.2016.1208072

Gibbs, G., & Simpson, C. (2005). Conditions under which assessment supports students' learning. *Learning and teaching in higher education, (1),* 3-31.

Goos, M. (2002). Understanding metacognitive failure. *Journal of Mathematical Behavior*, *21*(3), 283–302. http://doi.org/10.1016/S0732-3123(02)00130-X

Hertel, J. D., Cunningham, C. M., & Kelly, G. J. (2017). The roles of engineering notebooks in shaping elementary engineering student discourse and practice. *International Journal of Science Education*, 1-24. http://dx.doi.org/10.1080/09500693.2017.1317864

Hudesman, J., Crosby, S., Flugman, B., Issac, S., Everson, H., & Clay, D. B. (2013). Using formative assessment and metacognition to improve student achievement. *Journal of Developmental Education, 37*(1), 2.

Johnson, C. C., Peters-Burton, E. E., & Moore, T. J. (Eds.). (2015). *STEM road map: A framework for integrated STEM education*. Routledge.

Jonassen, D., Strobel, J., & Lee, C. B. (2006). Everyday problem solving in engineering: Lessons for engineering educators. *Journal of Engineering Education*, *95*(2), 139–151. http://doi.org/10.1002/j.2168-9830.2006.tb00885.x

Krippendorff, K. (2013). *Content Analysis: An introduction to its methodology.* Los Angeles, CA: Sage Publications, Inc.

Kelley, T. R. (2011). Engineer's notebook - A design assessment tool. *Technology & Engineering Teacher, 70*(7), 30-35. http://doi.org/10.1002/trtr.1351

Kolko, J. (2010). Abductive thinking and sensemaking: The drivers of design synthesis. *Design Issues*, *26*(1), 15–28. http://doi.org/10.1162/desi.2010.26.1.15

Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic inquiry.* Newbury Park, CA: Sage Publications, Inc.

National Academy of Engineering. (2004). The engineer of 2020: Visions of engineering in the new century. Washington, DC: The National Academies Press. http://doi.org/10.17226/10999

National Academy of Engineering and National Research Council. (2009). Engineering in K-12 education: Understanding the status and improving the prospects. Washington, DC: The National Academies Press. https://doi.org/10.17226/12635.

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: The National Academies Press. http://doi.org/10.17226/13165

Marcarelli, K. (2010). *Teaching science with interactive notebooks*. Thousand Oaks, CA.

Mathis, C. A., Siverling, E. A., Glancy, A. W., Guzey, S. S., & Moore, T. J. (2016). Students' use of evidence-based reasoning in K-12 engineering: A case study. Proceedings of the American Society for Engineering Education Annual Conference and Exposition. New Orleans, LA. Paper No. 16961, June 26-29.

McCormick, R. (1994). Learning through apprenticeship. In D. Blandow & M. J. Dyrenfurth (Eds.), *Technology education in school and industry: Emerging didactics for human resource development* (pp. 331–342). Berlin: Springer-Verlag.

Mentzer, N., Becker, K., & Sutton, M. (2015). Engineering design thinking: High school students' performance and knowledge. *Journal of Engineering Education*, *104*(4), 417–432. http://doi.org/10.1002/jee.20105

Moore, T. J., & Smith, K. A. (2014). Advancing the state of the art of STEM integration. *Journal of STEM Education: Innovations and Research, 15*(1), 5-10.

Moore, T. J., Stohlmann, M. S., Wang, H., Tank, K. M., Glancy, A. W., & Roehrig, G. H. (2014). Implementation and integration of engineering in K-12 STEM education. In Ş. Purzer, J. Strobel, & M. E. Cardella (Eds.), *Engineering in Pre-College Settings* (pp. 35-59). Purdue University Press.

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*. http://doi.org/10.17226/18290

Patton, M. Q. (2015). Qualitative research & evaluation methods (4th ed.). Thousand Oaks, CA: Sage Publications, Inc.

Pellegrino, J. W. (2012). Assessment of science learning: Living in interesting times. *Journal of Research in Science Teaching, 49*(6), 831-841. http://doi.org/10.1002/tea.21032

Perrenet, J. C., Bouhuijs, P. a. J., & Smits, J. G. M. M. (2000). The suitability of problem-based learning for engineering education: Theory and practice. *Teaching in Higher Education*, *5*(3), 345–358. http://doi.org/10.1080/713699144

Johnson, C. C., Peters-Burton, E. E., & Moore, T. J. (Eds.). (2016). *STEM roadmap: A framework for integrated STEM education. New York, NY: Routledge.*

Rider-Bertrand, J. (2012). Writing to learn with STEM notebooks. *Children's Technology and Engineering*, *17*(1), 6-9. http://dx.doi.org/10.1080/21532974.2016.1206491

Schreier, M. (2012). *Qualitative content analysis in practice.* Thousand Oaks, CA: Sage Publications, Inc.

Watkins, J., Spencer, K., & Hammer, D. (2014). Examining young students' problem scoping in engineering design. *Journal of Pre-College Engineering Education Research*, *4*(1), 43–53. http://doi.org/10.7771/2157-9288.1082

Welch, M. (1998). Students' use of three-dimensional modeling while designing and making a solution to a technological problem. *International Journal of Technology and Design Education, 8*(3), 241-260. http://doi.org/10.1023/A:1008802927817

Welch, M., Barlex, D., & Lim, H. S. (2000). Sketching: Friend or foe to the novice designer? *International Journal of Technology and Design Education, 10*(2), 125–148.

8(3), 241–260. http://doi.org/10.1023/A:1008991319644

Wheatley, L., McInch, A., Fleming, S., & Lord, R. (2015). Feeding back to feed forward: Formative assessment as a platform for effective learning. *Kentucky Journal of Higher Education Policy and Practice, 3*(2).

Author Information

Kerrie A. Douglas
Purdue University
School of Engineering Education
516 Northwestern Ave. Ste. 3500
West Lafayette, IN 47906,
U.S.A.
Contact e-mail: *douglask@purdue.edu*

Tamara J. Moore
Purdue University
School of Engineering Education
516 Northwestern Ave. Ste. 3500
West Lafayette, IN 47906
U.S.A.

Amanda C. Johnston
Purdue University
School of Engineering Education
516 Northwestern Ave. Ste. 3500
West Lafayette, IN 47906
U.S.A.

Hillary E. Merzdorf
Purdue University
School of Engineering Education
516 Northwestern Ave. Ste. 3500
West Lafayette, IN 47906
U.S.A.