EXPLORING FIRST GRADE STUDENTS’ PLANNING IN AN ENGINEERING DESIGN PROBLEM AND ITS RELATIONSHIPS TO ARTIFACT CONSTRUCTION AND SUCCESS:

A PILOT STUDY

A qualifying paper

submitted by

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Abstract

The purpose of this study was to explore how first grade students’ plan and solve an engineering design problem. It specifically analyzes children’s drawings of their planned solutions to the problem and how the drawings related to the engineering design problem requirements, the construction of the solutions, and the success of their solutions. First grade students participated in individual videotaped interview sessions where they engaged in drawing and constructing a solution to an engineering design problem. The data indicated that many students are able to draw plans for solutions that address the problem requirements, although not all students fully address all the requirements. The data also showed that many students could select materials that were most efficient for meeting the requirements of problem over materials that were less efficient. Just over half of the students created artifacts that closely matched their planned drawings indicating that first graders can carry most of their ideas from the planning of the solution to the actual constructions. However, there was a lack of data to draw conclusions about why participants chose to change their ideas between planning and construction. The data also did not indicate a clear relationship between the quality of students’ drawing of their planned solution and the success of their artifact. The results of this study suggest that planning prior to constructing an artifact is something that many first grade students can do but more research is needed to understand the characteristics and experiences of young students that differentiate their performance in planning and carrying ideas from planning to artifact construction.
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Introduction

The purpose of this study was to explore how first grade students’ plan and solve an engineering design problem. It specifically analyzes children’s drawings of their planned solutions to the problem and how the drawings related to the engineering design problem requirements, the construction of the solutions, and the success of their solutions. The research questions underlying this study focused on identifying the capabilities of young children when planning a solution to an engineering problem and describing the relationship between the children’s plans (the drawing of their solution) and their final constructed artifact. The study has the potential to broaden the understanding of nature of young children’ planning in solutions to engineering design problems, a relevant goal as more activity and curricula development includes engineering design problems for young children. Currently, there is a limited amount of information, often conflicting, about how young children should engage in engineering design that curriculum designers can draw on to base decisions of how to teach young children engineering design and what steps of the engineering design process young children can be expected to understand and utilize.

Engineering education at the Kindergarten through Grade 12 (K-12) level is a relatively new idea in the United States (US) educational system that brings the content and processes of the domain of engineering into elementary and secondary schools. Engineering education at the K-12 level is unique to the United States (US) and differs from other movements in science or mathematics education in that the impetus can be traced to the engineering community in higher education and in the workforce. In 1986, the American Society of Engineering Education (ASEE) commissioned a task force to look at college-level engineering education. This task force, which yielded the report *A National Action Agenda for Engineering Education* (American
Society for Engineering Education, 1987) includes one of the first calls to connect engineering education to K-12: “programs in mathematics and science, which prepare and motivate, the nation’s pre-college youth to seek engineering careers, must be strengthened” (p. 190). This call has been followed up in subsequent ASEE reports such as *Engineering Education for a Changing World* (Engineering Deans Council and Corporate Roundtable, 1994) and the National Academy of Engineering’s (NAE) recommendations in *Engineering Education: Designing an Adaptive System* (1995) and *Educating the Engineer of 2020* (2005). The motivation for ASEE’s call and for the National Academy’s concern for K-12 education can be linked to the declining enrollment in engineering at the college level (National Science Foundation, 2000) as well as the continuing constraint of educating engineers with the four year engineering program model (Grayson, 1993). This initial impetus has broadened to include technological literacy for all citizens (Pearson & Young, 2002) but workforce and enrollment issues are still of paramount importance for many.

Engineering design, the process by which engineers move from problem to a product or process that addresses the problem, is a fundamental component in the domain of engineering. Models of the engineering design process structure the process into different steps including: identify the need or problem, research the need or problem, develop possible solution(s), select the best possible solution(s), construct a prototype, test and evaluate the solution(s), communicate the solution(s), and redesign (Massachusetts Department of Education, 2001). The steps of the engineering design process prior to the actual construction of a prototype focus on identifying, understanding, and exploring the problem as well as planning a solution for it. For the purposes of this study, which is grounded in the domain of engineering, we are interested in the steps of the engineering design process that we are categorizing as planning steps (e.g. select
the best possible solution) or steps that provide information needed for planning a solution (e.g. identify the need or problem).

Understanding of the engineering design process steps is often a learning goal in much of the engineering education curricula and activities that are created for K-12 students. National and state standards that include the engineering design process (International Technology Education Association, 2002; Massachusetts Department of Education, 2001) vary significantly in their recommendations about what steps of the engineering design process young children should be learning. This lack of consensus makes it difficult to draw conclusions about what steps of the engineering design process should be included in engineering design activities for young children. While design activities have been part of K-12 education through other efforts such as teaching science through the design of artifacts (e.g. Fortus, Dershimer, Krajcik, & Marx, 2004; Kolodner et al., 2003; Penner, Lehrer, & Schauble, 1998) and technology education (e.g.Fleer, 2000a; Johnsey, 1995; Roden, 1999; Welch, 1999), we know very little about how young children engage in the engineering design process, specifically how they are able to plan and how planning relates to their solutions. In order to scaffold children’s learning of design, we need to understand how planning is used by young children and how we can design learning experiences that help them to see the value in developing planning skills such as identifying the problem requirements and drawing a representation of their planned solution.

This study’s focus on planning addresses the lack of a consensus in existing research in the areas of general problem solving and technology education about young children’s ability to plan and the role of planning in design. Planning, for the purposes of this study, is defined as the steps of the engineering design process students engage in prior to constructing a prototype to specify their design idea. Research in problem solving (Gardner & Rogoff, 1990; Gauvain &
Rogoff, 1989) using general, well-defined problems demonstrates that six and seven year old students (first grade age) are able to plan solutions when planning adds value to the outcome of a task -- for example planning was useful to students when it was important to make no wrong turns when solving a maze. Within the area of technology education, a movement in the United Kingdom (UK), Australia, and Canada (Anning, 1994; Roden, 1995; Welch, 1999), researchers are divided about students’ ability to engage in planning while they are designing. A number of studies (Johnsey, 1995; Rogers & Wallace, 2000; Welch, 1999) show that students do not spontaneously engage in planning when designing and that their plans do not have a strong resemblance to their final construction. Alternatively, there have been findings that young students can make plans that resemble their final creation (Fleer, 2000b) and that planning emerges as students progress through primary/elementary schooling (Roden, 1995, 1999). Within technology education, the research projects were all conducted within classroom settings; therefore, they include a number of confounding variables (peers, classroom atmosphere, teacher’s understanding of design, curricula, access to materials) that make it difficult to fully interpret the results. Moreover, there have been no efforts to date that look specifically at whether children’s drawings of their plans address the problem presented.

Understanding if young children can identify problem requirements and draw a potential solution is crucial for thinking about the role planning can have for young children in engineering design activities and the form it can take. For example, if young children are unable to understand implicit problem requirements on their own than these elements will need to be made explicit by the activity and the teacher. In addition, there has also been no exploration of the relationship between plans and successful solutions to see if planning helps young children
solve design problems. Understanding if planning helps young children solve design problems is critical as we think about teaching them the value of planning their ideas.

This pilot study is a first step in exploring how first grade students plan solutions to engineering design problems and how their planning is related to their constructed artifact and its success. It looks at three main questions:

1. How do students’ drawing of their planned solution to an engineering design problem address the problem requirements and constraints?
2. What is the relationship between first grade students’ drawing of their planned solution and their constructed artifact?
3. What is the relationship between first grade students’ drawing of their planned solution and the success of their constructed artifact?

Background

The domain of engineering

To fully understand how children engage in engineering design, the domain of engineering and the role of design within that domain should be understood. The terms engineering and engineer have several meanings in the English language. Train operators are often referred to as engineers (Knight & Cunningham, 2004) and any solutions that are artfully constructed are referred to as “engineered” (engineering, n.d.). However, none of these meanings refer specifically to the conceptual field that young children deal with in engineering education. Hence it is important for this study to ground our understanding of engineering in what is particularly pertinent for the field of engineering education. In the field of mathematics education, Chevallard (1997) has referred to the process of didactical transposition, which involves the transformation process that objects of knowledge go through in order to become
objects of teaching. Chevallard (1997) claims that there is a distance between the object of knowledge and the teaching object. Chevallard’s framework is important to bear in mind as we consider both the necessary distance and the transformation between engineering as an object of knowledge (i.e., engineering as a discipline) and engineering as an object of teaching (i.e., engineering education). Both are not and cannot be the same.

For the purposes of this study, the domain of engineering refers to the work that professional engineers engage in and informs the coursework provided by higher education institutions that provide degrees in engineering. Engineering is defined in the dictionary as:

The application of scientific and mathematical principles to practical ends such as the design, manufacture, and operation of efficient and economical structures, machines, processes, and systems. ("Engineering", n.d.)

This definition encompasses the general understanding of the domain of engineering. It highlights that engineering includes math and science and that engineers generate products or processes. However, this definition makes it easy to assume that engineering is simply the application of the knowledge from the domains of math and science. This assumption is problematic in thinking about bringing engineering into K-12 classrooms. If we assume that engineering is simply the application of math and science then the implication could be that students need no other knowledge to engage in engineering other than math and science. However, as will be presented below, exploring definitions and analyses of the domain of engineering yields an understanding of engineering as having a unique body of knowledge and that design is a fundamental part of the domain.

Herbert Simon, a noted researcher in computer science and psychology, classifies engineering as one of the sciences of the artificial, highlighting that artificial means “produced
by art not by nature” (Simon, 1996, p. 4). Being a science, by Simon’s definition, means that engineering has unique knowledge, just like physics or chemistry. Engineering’s unique knowledge encompasses the engineering sciences (e.g., mechanics of solids, fluid mechanics, thermodynamics, transport phenomena, electromagnetism, material structures and properties; (Committee on Evaluation of Engineering Education, 1955) which take principles of math and science and create new models for specific artifacts. The second term in Simon’s classification is artificial. Being artificial (as opposed to natural) means that the domain focuses on the human synthesis of products or processes. Artificial domains, by Simon’s definition, are characterized by design – the process by which designers take a problem or need and conceive and disseminate a solution. Engineers are certainly not the only “professional designers” (Simon, 1996, p. 111) but design dominates the work of a majority of engineers.

Simon’s theoretical assertions regarding the nature of engineering and the significance of design are echoed by Sunny Auyang’s analysis of the engineering profession in her book, Engineering: An Endless Frontier (2004). Auyang (2004) concludes from her observations, interviews, and research that modern engineering is comprised of three activities: Science (engineering science), Design, and Management. Her analysis of the workforce leads her to conclude that design and development is the work that most engineers are engaged in (Auyang, n.d.), although many engineers do engage in basic and applied research (Science) and management/entrepreneurial work.

Within the engineering community, descriptions of the domain highlight that design is a significant and distinguishing element of engineering. Bordogna (2008) has contrasted engineering with science, focusing on design: “Scientists investigate what is; they discover new knowledge by peering into the unknown... Engineers create what has not been; they make things
that have never existed before” (Engineering Pathways, 2008). Similarly, Wulf (2002), then president of the National Academy of Engineering, gave a speech that included this explanation of engineering, by saying that “Science is analytic. Science is concerned with understanding nature, with understanding what is. Engineering is about designing, creating solutions to human problems.” Wulf puts forth an operationalized version of his definition: engineering is to “design under constraint.”

While design is not the only activity that engineering includes, it has been identified as a fundamental and defining part of the domain in the theoretical definitions as well as in the explanations of engineers. Hence, we would expect engineering design to be a significant part of K-12 engineering education and indeed many K-12 engineering education curricula engage students in engineering design ("Engineering is Elementary", n.d.; Project Lead The Way, n.d.; The Infinity Project", n.d.). If engineering design is a significant part of K-12 engineering education, we need to explore engineering design as defined within the domain of engineering to understand the importance of planning.

Theoretical Framework

*Engineering design*

Having established the importance of engineering design within the domain by examining theoretical and domain definitions of engineering, it is necessary to define what is meant by engineering design. Engineering design problems are inherently ill-structured or ill-defined — that is, they have vaguely defined or unclear goals, unstated constraints, multiple solutions with multiple solution paths, and possess multiple or unknown criteria for evaluating solutions (Jonassen, Strobel, & Lee, 2006). This is in contrast to well-structured problems, like arithmetic problems, that have all of the needed information present to arrive at a single solution.
through a series of known rules and processes. Arranging problems on a continuum from well-structured to ill-structured, Jonassen (2004, pp. 2-3) classifies design problems, such as engineering design problems, as the most ill-structured. Design is a general term that can be described as “to plan and fashion artistically or skillfully” (design, n.d.). Engineering design refers specifically to the design that engineers engage in to solve an engineering design problem.

Models of the engineering design process

The engineering design process is a model of the steps engineers proceed through to work from a problem to a designed artifact. Well-structured problems have algorithms that can be used to arrive at solutions. Models of design processes provide a framework for people to solve ill-structured problems (Jonassen, 2000). Within the domain of engineering, models of the engineering design process have evolved over the last 50 years (Roozenburg & Cross, 1991). Figure 1 shows a representation of the engineering design process created by German engineers Pahl and Beitz (1984).
Figure 1. A consensus engineering design process model (Pahl & Beitz, 1984).
This model of the engineering design process divides the design process into five main sections: clarification of task, concept generation, embodiment design, detail design, and evaluation. While the horizontal lines are meant to indicate that the process is not linear and any step can be revisited at any time, it should be noted that the bulk of the steps occur before the construction of the prototype, demonstrating that the majority of the process is expected to take place before anything is constructed. Key actions in the preliminary steps of the design process include “Determining the Need” by “Determining Functional Requirements and Constraints.”

Requirements in the engineering design process are defined as the necessary elements of the final product. For example, in the design of a new car a requirement might be to achieve a fuel efficiency of 40 miles per gallon. Constraints in the engineering design process are the restrictions or limiting elements. In the case of the new car, constraints might include using existing parts from the car manufacturer. It should be emphasized that requirements and constraints are often unstated (Jonassen, Strobel, & Lee, 2006) or implicit, hence why steps of the engineering design process direct engineers to determine the requirements and constraints.

Following the identification and specification of the need, the Pahl and Bietz model of the engineering design process looks for engineers to engage in searching for possible solutions, evaluating their designs, and creating progressively more detailed designs before moving into prototyping and testing. The preliminary and detailed designs, likely presented as drawings or CAD models, can be evaluated for how they meet the requirements and constraints.

The Pahl and Beitz model is categorized as a “consensus” model as it evolved along with other similar models that described engineering from a systems engineering perspective where design agreement must be reached before proceeding with the final detailed design. Systems engineering is concerned with the creation of large and complex products or processes (where
there is little room for trial and error with the full scale artifact). Other consensus models, such as French’s (1998), break the engineering design process into greater or fewer steps (see Figure 2) but they all have the same basic arrangement of working from specifying the need to general designs to specific designs to prototyping and testing and final design specifications.

Planning, defined for this study as the steps in the design process that precede prototyping, is a hallmark of consensus models as engaging in trial and error with a prototype is often unfeasible or very expensive with large products or processes. Hence, it seems crucial that if children are learning engineering design that they learn to engage in planning.

Figure 2. French’s (1998, p. 2) consensus model of the engineering design process.
There is some debate regarding how generalizable models of the engineering design process are across different branches of engineering (Lawson, 2005). There is also some debate regarding the prescriptive nature of consensus design process models, which some find of limited use in helping engineers think about design problems (Roozenburg & Cross, 1991). These debates are ongoing but current research in engineering design at the college and professional levels is not mired in that debate and uses its own modified steps of the consensus model of the engineering design process (Identifying a Need, Problem Definition, Gathering Information, Generating Ideas, Modeling, Feasibility Analysis, Evaluation, Decision, Communication, Implementation) to code/categorize behavior of engineers engaged in design (Altman et al., 2007; Altman, Cardella, Turns, & Adams, 2005; Altman & Turns, 2001). This approach has been fruitful in helping to understand which engineering design process steps expert designers spend more time in (versus novice designers) which aids engineering design educators in understanding what steps of the engineering design process need to be emphasized in engineering design courses (Altman, Cardella, Turns, & Adams, 2005). Similarly, for this study we will operate under the assumption that the engineering design process model is a useful structuring element for thinking about how children engage in design. However, to develop a set of steps that are more relevant for young children, we will look specifically at engineering design process models that have been created for use with children.

*Representation in Engineering Design*

It should also be noted in these models of the engineering design process that the final output as well as the output of early steps of the process is a representation of the engineer’s idea (typically a drawing or set of drawings) that specifies the solution generated. Pahl and Dietz’s (1984) model (see Figure 1) specifies that representations are created in reference to detailed
final drawings. French’s model (see Figure 2) specifies that working drawings are created at the conclusion of the design. Clive Dym’s analysis of engineering design highlights that the key element of engineering design is representation (1994, p. 1). He emphasizes that the most significant product of engineering design is not the artifact that the end user interacts with, but the multiple representations of the artifact (drawings, mathematical equations, text) that can be used to detail the design so that it can be manufactured or recreated. This sentiment has been recently revisited in Visser’s analysis of design as a cognitive activity. “Designing consists in specifying an artifact, for example a machine tool – not in its implementation, its fabrication in the workshop. The result of design is a representation, the specifications of the machine tool” (Visser, 2006, p. xvi). Visser also emphasizes that representations are used throughout the design process in planning and analysis. While representation is acknowledged as an important output of the engineering design process, this study, with its scope of planning, will focus only on students’ initial drawings that indicate their preliminary ideas for a solution. However, this study acknowledges the importance of representations and drawings by highlighting this activity within children’s planning process.

*K-12 Engineering Education*

The models of the engineering design process that are relevant for real world engineering are not directly usable in K-12 classrooms, which lack the structure of an engineering firm, the extended timeline with which to engage in design, and whose students often have limited math and science knowledge to be utilized in the engineering design process. Chevallard (1991) has presented the idea of didactic transposition, the process by which subject (domain) knowledge is transposed into school knowledge. It can be argued that attempts to find the best ways to transpose engineering design knowledge into objects of teaching are happening in the world of
K-12 engineering education and occurring in different ways at the national, state, and project level. Despite the plethora of engineering curricula (e.g. "Engineering is Elementary", n.d.; Green et al., 2002; Project Lead The Way, n.d.; The Infinity Project", n.d), there is not a single translation of the engineering design process model for K-12 students nor is there a single view about what steps of the engineering design process young children should learn.

At the state level, the Massachusetts Curriculum Frameworks have worked to outline what engineering for children entails. They propose a single engineering design process model for K-12 (see Figure 3) that is arguably a derivation of a consensus model (Pahl & Beitz, 1984) of the engineering design process.

1. Identify the need or problem
2. Research the need or problem
   * Examine current state of the issue and current solutions
   * Explore other options via the internet, library, interviews, etc.
3. Develop possible solution(s)
* Brainstorm possible solutions
* Draw on mathematics and science
* Articulate the possible solutions in two and three dimensions
* Refine the possible solutions
4. Select the best possible solution(s)
  * Determine which solution(s) best meet(s) the original requirements
5. Construct a prototype
  * Model the selected solution(s) in two and three dimensions
6. Test and evaluate the solution(s)
  * Does it work?
  * Does it meet the original design constraints?
7. Communicate the solution(s)
  * Make an engineering presentation that includes a discussion of how the solution(s) best meet(s) the needs of the initial problem, opportunity, or need
  * Discuss societal impact and tradeoffs of the solution(s)
8. Redesign
  * Overhaul the solution(s) based on information gathered during the tests and presentation

Figure 3. The Engineering Design Process model included in the Massachusetts’ Technology/Engineering Frameworks (Massachusetts Department of Education, 2001).

Even though engineering is included in the Massachusetts Curriculum Frameworks, the Massachusetts standards for Pre-Kindergarten through Grade 2 (PreK-2) do not require students to learn the engineering process. The Massachusetts engineering design standard for PreK-2 requires that students learn to “identify tools and simple machines used for a specific purpose, e.g., ramp, wheel, pulley, lever” and “Describe how human beings use parts of the body as tools (e.g., teeth for cutting, hands for grasping and catching), and compare their use with the ways in which animals use those parts of their bodies” (p. 85). Understanding and using the engineering design process is not introduced until the 6-8 grade level in the Massachusetts State Frameworks. This view of engineering design for children would lead to the conclusion that K-2 students are not yet capable of engaging in solving engineering design problems.

In contrast, at the national level, the Standards for Technological Literacy (STL) (International Technology Education Association, 2002) propose that students learn basic components of engineering design as early as Kindergarten. The STL do not propose a specific model of the design process but their standards outline design process skills that are used in the
engineering design process. The K-2 STL standards for design are presented in the Design section under Standard 9:

Standard 9 – Students will develop an understanding of engineering design…

A. The engineering design process includes identifying a problem, looking for ideas, developing solutions, and sharing solutions with others.

B. Expressing ideas to others verbally and through sketches and models is an important part of the design process. (p. 99)

Examining these standards we see that the STL assert that K-2 students should be engaged in understanding many of the engineering steps of the engineering design process. Specifically, the STL standards specify: “identifying a problem, looking for ideas, developing solutions, and sharing ideas with others” (p. 99). The STL also state that K-2 students should be engaged in representing their ideas through drawings and models. Notably missing from the standards for K-2 are the elements of testing and redesign (evaluation) that are presented in the STL standards for grades 3-5 level and creating representations of their final solution which is presented at the 9-12 level. However, the STL assert that K-2 students should be doing many steps of the design process, including some planning (“developing solutions”) and drawing (“Expressing ideas to others verbally and through sketches and models is an important part of the design process”).

Engineering is Elementary ("Engineering is Elementary", n.d.), is one of the few curricular projects that includes resources for teaching engineering design to early elementary grades (Grades 1-2). This program created their own representation of the design process that appears to consolidate the number of steps in the design process and the language involved (see Figure 4). They highlight their simplification (Cunningham & Hester, 2007) of the engineering design process model as a feature of their program but have no research-based evidence for the
choices they have made. Their model does include 3 steps of planning (Ask, Imagine, Plan) and even suggests that students identify constraints and draw a plan with the materials they will need.

**Figure 4.** Engineering is Elementary's Engineering Design Process Model for Early Elementary.

ASK
* What is the problem?
* What have others done?
* What are the constraints?

IMAGINE
* What are some solutions?
* Brainstorm ideas.
* Choose the best one.

PLAN
* Draw a diagram.
* Make lists of materials you will need.

CREATE
* Follow your plan and create it.
* Test it out!

IMPROVE
* Talk about what works, what doesn’t, and what could work better.
* Modify your design to make it better.
* Test it out!
The lack of consensus of what steps of the engineering design process young children should be engaged in forms a fractured and disjointed picture of what engineering design should look like in the early elementary classroom. This presents a challenge for engineering education curriculum developers as it is unclear what engineering design problems should be required of young students or if they should even be engaged in design problems. In addition, it presents a challenge for this study to select an appropriate engineering design process model. Therefore, for the purposes of this study, based on the Standards for Technological Literacy and Engineering is Elementary, we will evaluate if young children can engage in planning actions during design. It is not in the scope of this study to evaluate or generate whole models of the engineering design process for children. Table 1 lists all the planning steps for the engineering design process that first grade students would be expected to engage according to the Standards for Technological Literacy (International Technology Education Association, 2002) and Engineering is Elementary ("Engineering is Elementary", n.d.). The Massachusetts engineering design process model (Massachusetts Department of Education, 2001), which is not required for PreK-2 students, is included because of its similarity to the real world models of the engineering design process.
Table 1. Planning steps described in MA Curriculum Frameworks, Standards for Technological Literacy and Engineering is Elementary.

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<thead>
<tr>
<th>Massachusetts Engineering Curriculum Frameworks</th>
<th>Standards for Technological Literacy</th>
<th>Engineering is Elementary</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Identify the need or problem</td>
<td>The engineering design process includes identifying a problem…</td>
<td>ASK</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* What is the problem?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* What have others done?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* What are the constraints?</td>
</tr>
<tr>
<td>2. Research the need or problem</td>
<td>The engineering design process includes …looking for ideas</td>
<td>IMAGINE</td>
</tr>
<tr>
<td>* Examine current state of the issue and current solutions</td>
<td></td>
<td>* What are some solutions?</td>
</tr>
<tr>
<td>* Explore other options via the internet, library, interviews, etc.</td>
<td></td>
<td>* Brainstorm ideas.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* Choose the best one</td>
</tr>
<tr>
<td>3. Develop possible solution(s)</td>
<td>The engineering design process includes …developing solutions</td>
<td>PLAN</td>
</tr>
<tr>
<td>* Brainstorm possible solutions</td>
<td></td>
<td>* Draw a diagram.</td>
</tr>
<tr>
<td>* Draw on mathematics and science</td>
<td></td>
<td>* Make lists of materials you will need</td>
</tr>
<tr>
<td>* Articulate the possible solutions in two and three dimensions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Refine the possible solutions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Select the best possible solution(s)</td>
<td>Expressing ideas to others verbally and through sketches and models is an important part of the design process.</td>
<td></td>
</tr>
<tr>
<td>* Determine which solution(s) best meet(s) the original requirements</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For this study, a list of steps was synthesized from all 3 engineering design process models that first grade students could be expected to engage in. They include:

- Identify the problem (in a given engineering design problem)
- Identify the problem requirements
- Identify the problem constraints
- Conduct Research (look for ideas)
- Brainstorm multiple ideas for a solution
- Select the best idea from brainstorming
- Create a plan (a 2-D or 3-D representation) of their best idea that contains the materials to be used
However, to allow for the development of a task that could be completed in a clinical interview setting in the amount of time designated by school administrators (20 minutes), three elements of planning were selected: (1) identification of problem requirements, (2) identification of the problem constraints and (3) creation of a plan with materials. This selection excludes steps of research, brainstorming multiple ideas, and the selection of the best idea for brainstorming, which are traditionally time consuming. Time was of critical importance so that students also had time to construct their solution, thus allowing for the relationship between drawing and their constructed artifact could be explored.

*Young Children’s Planning*

Research on young children’s planning was investigated to establish what is currently known about children’s planning in the general area of problem solving, in learning by design projects, and in design and technology research.

*Children’s Planning in Problem Solving Research*

A commonly used definition of planning within the problem solving literature is planning as “predetermination of a course of action aimed at achieving some goal” (Hayes-Roth & Hayes-Roth, 1979). Looking at general (non domain specific) problems, researchers have documented that first grade students (6 and 7 year olds) are on the cusp of being able to successfully plan when properly motivated and that their planning is related to their success on a given task. Gardner and Rogoff (1990) studied children’s ability to plan routes when presented with mazes and different requirements (speed vs. accuracy). They worked with children between the ages of 4-10 and found that older children (7-10 year olds) planned more often when accuracy was a requirement, while younger children were unlikely to change their strategy regardless of the
requirements. Gauvain and Rogoff (1989) also found that older children (7-10 year olds) were better able to plan routes (for a model grocery store shopping trip) and that children who planned in advance produced more efficient routes. These results would support the idea that first grade students are able to complete planning tasks, such as those that might be required of them in an engineering design task like the one presented to them in this study. However, in previous research, the problems that have been presented to students are well defined and the question that remains for this present study is whether the context of an engineering design problem impacts students’ ability to plan. In addition, the methodology of a clinical interview used in the problem solving literature is useful for this study to help to isolate students’ capabilities from classroom complexities that is present in other research.

Learning through Design: Identification of Problem

One of the elements of planning in engineering design that was highlighted for this study is students’ ability to identify problem requirements. Students’ identification of the problem is key to their ability to plan the solution. Penner, Gildes, Lehrer, and Schauble’s work on designing a model of the elbow with first and second graders (Penner, Giles, Lehrer, & Schauble, 1997) and third and fourth graders (Penner, Lehrer, & Schauble, 1998) required students to identify the requirements for the elbow (the problem requirements of the flexing of the elbow and the constraining of it’s motion to mimic the elbow’s movement). These researchers’ work does not use the design process in their teaching intervention but focuses on using the creation of models to understand science concepts.

Penner and his colleagues reported that the younger children (grades 1 and 2) initially paid more attention to perceptual qualities (hands, veins) than to functional qualities in their elbow designs than did the older children (grades 3 and 4). Younger children also initially only
paid attention to one dimension of the elbow’s movement (flexing) and did not address the elbow’s motion in other dimensions. These results indicate that first grade students may have difficulty identifying the requirements of an engineering design problem, which would impact their ability to plan a solution. Therefore, in the study reported in this paper we will quantify whether or not students are able to identify the requirements of the problem presented.

Children’s Planning in Research in Design & Technology (D&T) Education

To date, engineering education has not generated research in the area of young children and the engineering design process. However, D&T has long been a subject area in the national curriculum of the UK, Australia, and Canada (Department for Education and Skills & Qualifications and Curriculum Authority, 2004; Newfoundland and Labrador Department of Education, 2007) and also includes steps of a design process (though not connected specifically to engineering design) in their required learning goals for students as young as 5. Hence, a number of researchers have looked at how students plan when engaged in solving design problems.

Spontaneous Planning

Researchers in technology education in the UK and Australia have looked at whether children naturally plan when engaged in creating solutions to design problems. Their results, all based on classroom observations, generally indicate that young children do not plan. However, a single research study, that was carried out by Roden (1999), indicates that planning may develop with age, emerging at age 7.

Johnsey (1995) looked to categorize the students’ behaviors when they engage in design tasks and see how they changed across ages. To do so he conducted videotape analysis of
students 4-10 years old engaged in design tasks in UK classrooms. He coded each behavior and the time it occurred into a system of design process behaviors that he developed based on an unidentified design process model and pilot study work. He used the codes and times to generate graphs of the steps students were engaged in during the design process. His codes/behaviors included:

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IDE</td>
<td>Identifying the potential for a design activity.</td>
</tr>
<tr>
<td>INV</td>
<td>Investigating the context from which the design task will emerge.</td>
</tr>
<tr>
<td>CLA</td>
<td>Clarifying the meaning and implications of the design task.</td>
</tr>
<tr>
<td>SPE</td>
<td>Specifying the requirements of the outcome of the task.</td>
</tr>
<tr>
<td>GEN</td>
<td>Generating ideas and solutions related to the task.</td>
</tr>
<tr>
<td>RES</td>
<td>Researching the problem and its possible solutions.</td>
</tr>
<tr>
<td>MOD</td>
<td>Modelling ideas for possible outcomes.</td>
</tr>
<tr>
<td>PLA</td>
<td>Planning to produce the outcome.</td>
</tr>
<tr>
<td>ORG</td>
<td>Organising resources (materials, tools, space and time).</td>
</tr>
<tr>
<td>MAK</td>
<td>Making or producing the outcome, including making improvements.</td>
</tr>
<tr>
<td>EVA</td>
<td>Evaluating the developing product, the procedures involved and the completed outcome. (The evaluation of other’s designed products was considered to be included in Identifying, Investigating and Researching.)</td>
</tr>
<tr>
<td>O/T</td>
<td>Off task</td>
</tr>
</tbody>
</table>

*Figure 5. Johnsey’s Design Process Behavior Classifications.*

Johnsey found that students naturally engage in “Make-Evaluate-Make” processes (MAK, EVA, MAK) but did not generally engage in planning ideas thoroughly before engaging with the materials. However, his results are difficult to interpret as the number of participants in his study and their exposure to design curricula is not well described. He does indicate that most activities took place with very little teacher interaction or intervention.
Researchers who have investigated planning with older children have similar findings to Johnsey’s. McCormick, Hennesey, and Murphy (1993) carried out observations of two 13 year old female dyads working together on the design of a kite. The researchers found that the students did not engage in a linear design process, and their process was not informed by planning. Similarly, Welch and Lim (2000) looked at how dyads of grade 7 students who had had no prior instruction in design approached a design task of constructing a paper tower of 100 cm. Through video and audiotape analyses of students working, Welch and Lim conducted protocol analysis of the steps of the design process (i.e., Generate, Understand, Model, Build, Evaluate) that the students naturally engaged in. They constructed graphs of the students design processes from their protocols and concluded that Planning and Modeling of the design process are unnatural for novice designers.

However, Roden (1999) looked at design process strategies longitudinally across 5-7 year olds in UK classrooms engaged in D&T projects and found planning to be emergent at the upper age level. Roden’s work focused on strategies and the dyad and group level rather than the individual (this perhaps led him not to include the size of the sample in his paper). He developed a taxonomy of group problem solving strategies through qualitative analysis techniques (Systems Networks) of his observations of children engaged in design. He used audiotape and field notes to look for specific strategies in his taxonomy (Personalisation, Identification of Needs and Wants, Negotiating and Responding to the Task, Focusing on the task or on the tools and materials, Practice and Planning, Identifying difficulties, Talking self through problems, Tackling Obstacles, Sharing and Co-operating, Panic or Persistence, and Showing and Evaluating). He found that students were able to engage in more sophisticated strategies (i.e., Focusing on Tasks or Materials or Identifying Obstacles) and that many of their strategies
evolved (i.e., into Practice and Planning) while other less sophisticated strategies diminished in use (i.e., Personalization and Talking to Self). Roden does not describe the classroom instruction that went on during these activities. It is implied that the instruction that took place is the implementation of the UK Design & Technology National Curriculum, but given the variability of teachers’ understanding of how to teach this subject matter (Anning, 1994), it is unclear whether these strategies developed due to age or instruction.

The research on children’s spontaneous planning was all conducted within the complexity of classroom environments where variables such as the partnering of students, access to materials, material type, and teacher’s knowledge of design make it difficult to ascertain which aspects influenced children’s decision to not plan. The research in problem solving and children’s planning (Gardner & Rogoff, 1990; Gauvain & Rogoff, 1989) indicates that children are able to plan when planning has value – which raises the question whether students see value in planning for design problems in the settings where students were found to not engage in planning. Moreover, while previous research indicates that children may not be likely to spontaneously plan in solving design problems, for this study, planning has been identified as an important component of the engineering design process. Hence, for this study, we will require students to plan and look at their planning or absence of it in the context of a clinical interview to minimize external factors.

Drawing

The creation of representations has been identified as an important output of steps of the engineering design process (Dym, 1994; Visser, 2006). Research specifically looking at how students drawings of their plans for their intended solution is divided on whether young children can engage in drawing plans for their solutions. Rogers and Wallace (2000) did extensive
observations of a classroom of 5 year olds in Australia that has a D&T curriculum strand as part of their educational requirements. This qualitative study based on observations and collecting student work primarily focused on a single project where students were asked to make a vehicle with wheels and were asked to create plans that included a drawing of their vehicle and selecting materials. The researchers found little connection between students’ drawn plans and their built objects. The researchers did not develop a quantitative measure for comparing the drawn plans with the built objects so it is impossible to ascertain whether students changed their ideas significantly or slightly. The study also does not describe whether the students were familiar with the materials they were using. In addition, the researchers also reported that the students indicated that they did not understand how their drawing (plan) was supposed to relate to their built object. They highlight that they believed the teacher in the classroom could have been more explicit to help the students understand the role of drawing in the design process.

In contrast, Fleer (2000b) looked at 16 children between the ages of 3 and 6 building animals or houses out of craft materials and found that they were able to plan their creations by drawing a picture of the animal or house with the materials they intended to use. Fleer looked at four categories of matching between drawing and artifact (naming of animal or house, materials they intended to use, configuration and joining of materials, overall placement). She found that a majority of students’ designs did correlate with their plans but that their plans were easily altered by the proximity and availability of materials as well as other students’ ideas. Fleer suggested steps teachers could take to help students see the value of their planning, such as only supplying the materials students’ show in their drawing.

The contrasting findings of these two studies make it impossible to have a clear conclusion about the ability of young children to draw their plans. This gap in the research
leaves room for this study to investigate if young children are able to draw a plan for a solution to an engineering design problem. None of the previous studies has defined measures to quantify the drawing or artifact, so it is impossible to determine how well students were able to plan in relation to the problem requirements and the relationship between a successful artifact and its plan. Hence, for this study, measures were developed to quantify the plan and the artifact to better understand how students changed their ideas and how well they were able to address problem requirements and constraints in the planning phase.

Methodology

Research Questions

The goal of this study was to increase our understanding of young children’s planning in engineering design problems. This study was designed to answer three questions:

1. How do students’ drawing of their planned solution to an engineering design problem address the problem requirements?

2. What is the relationship between first grade students’ drawing of their planned solution and their constructed artifact?

3. What is the relationship between first grade students’ drawing of their planned solution and the success of their constructed artifact?

The first question aims to describe how students’ drawing of their planned solution accounts for the problem requirements. Research to date has not looked at whether students can develop solutions on paper that address the problem requirements and constraints to validate that planning on paper is a viable method for young children to approach a (design) problem. Related research in design-based learning (Penner, Giles, Lehrer, & Schauble, 1997; Penner, Lehrer, & Schauble, 1998) suggests that students may have trouble identifying implicit requirements. The
second question explores how the drawing of the planned solution compares to the constructed artifact to explore how students’ ideas persist from drawing to artifact. Previous research in this area (Fleer, 2000b; Rogers & Wallace, 2000) provides us with conflicting findings about the relationship between drawing and artifact. This study’s interview context will add to this body of knowledge. The final research question looks to characterize how the drawing of the planned solution relates to success of the constructed artifact. Through this question, we will explore if successful planning predicts success in the design challenge to see how directly valuable planning is related to success for young children. In this study, success is defined as the construction of an artifact that completes the design problem in a designated period of time. We acknowledge that there are multiple actions that could be included in planning (gesturing, thinking, measuring), however for this study we will focus exclusively on the students’ drawing as the representation of their planning.

Participants

Participants were solicited from four first grade classrooms in an upper middle class suburban Boston-area elementary school. Seventy-six first grade students were invited to participate and 31 (16 females and 15 males) students consented to fully participate in the research study.

Task Design

The Trapped Key task served as the single engineering design task presented to students in a clinical interview setting. The task required students to design a tool to retrieve a set of two keys attached to a key ring from the bottom of a clear Plexiglas box (23”x4.5”x4.5”; see Figure 6). The box was not fixed to the floor and the top was fully open. Students were provided with eight materials (12” pipe cleaners, 12” wooden dowel rods [sticks], plastic spoons, unsharpened
pencils, string, paperclips, round and bar magnets, and tape) as well as scissors to use to design and construct a tool to retrieve the keys.

Figure 6. Trapped Key Task and Materials.

The task design was loosely derived from the work of Altman and her colleagues (Altman et al., 2007) that looked at the performance of expert and novice engineers on a single design task (a playground). Their highly open-ended task required participants to design the equipment and layout of a playground. Altman’s playground task involved engineers using a range of knowledge they were expected to already have to create a playground design. In the Trapped Key task, the keys and construction materials were thought to be familiar to most first grade students and the task of retrieving an item from an awkward location was thought to be understandable for children of this age.

Engineering design problems are described as ill-defined, meaning they have unclear goals, unstated constraints, multiple solutions with multiple solution paths, and multiple or unknown criteria for evaluation of solutions (Jonassen, Strobel, & Lee, 2006). The Trapped Key task was designed to be a modified engineering design problem, with a better defined goal, to
work within the context of the 20 minutes limited time available in the interview. The task was also designed to focus on planning and the relationship between planning and success. Therefore, students were given the problem and not required to engage in formal research, brainstorming, the creation of multiple solution ideas, or the selection of a single best idea, in order to ensure that all students were able to plan and construct a solution in the designated time. However, the task was designed for students to determine **unstated requirements and constraints**.

It is important to highlight that both the requirements and constraints were implicit, and never made explicit to children. Therefore, one of the challenges of the task for children was being able to identify and address these constraints and requirements. Table 2 illustrates the structure of the *Trapped Key* Task as an engineering design problem using Jonassen’s (2006) definition of an engineering design problem as a guide.

*Table 2. Structure of *Trapped Key* Task as an engineering design problem.*

<table>
<thead>
<tr>
<th>Goal (Problem):</th>
<th>Stated/Explicit- Retrieve a set of keys from the Plexiglas box</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirements:</td>
<td>Unstated/Implicit –</td>
</tr>
<tr>
<td></td>
<td>Conceptual - The tool must address: (a) length and (b) key acquisition</td>
</tr>
<tr>
<td></td>
<td>Construction -</td>
</tr>
<tr>
<td></td>
<td>- The tool must reach a minimum length of 23”</td>
</tr>
<tr>
<td></td>
<td>- The tool must fit into the opening of the box 4.5” x 4.5”</td>
</tr>
<tr>
<td></td>
<td>- The tool must be sturdy</td>
</tr>
<tr>
<td>Constraints:</td>
<td>Stated/Explicit – Use the materials presented</td>
</tr>
<tr>
<td></td>
<td>Unstated/Implicit - Limitations of the materials</td>
</tr>
<tr>
<td></td>
<td>- Limitations of the box dimensions</td>
</tr>
<tr>
<td>Solution Paths:</td>
<td>The materials presented for the task allowed for multiple ways of acquiring the keys as well as multiple ways of combining materials to create a tool long enough to reach the bottom of the box</td>
</tr>
<tr>
<td>Criteria for Evaluation of Solution:</td>
<td>Stated/Explicit – Retrieval of keys</td>
</tr>
<tr>
<td></td>
<td>Unstated/Implicit – Time to retrieve keys</td>
</tr>
</tbody>
</table>

The requirements are divided between conceptual requirements, which focus on the big ideas for the problem and construction requirements, which are related to the specific configuration and dimensions of the box and the materials. This designation was made to create a framework to
help differentiate whether students understood the big ideas of the problem (as stated) and whether they accounted for the physical environment and materials (which they could see).

The materials presented to students were selected to give students a combination of ideal and non-ideal materials (see Tables 3 and 4) for the task to allow for multiple solutions paths as well as to explore how well students understood the problem requirements. For example, students were presented with 12” dowel rods and 7 3/8” pencils. Understanding the requirement of length would make the selection of the longer dowel rods more useful. Similarly, magnets and spoons could both be used to pick up keys off the floor, but the narrow box makes it impossible to get the spoons under the keys whereas magnets can pick up the keys from multiple angles or positions.

*Table 3.* Ideal and Non-Ideal Materials for Length.

<table>
<thead>
<tr>
<th>Ideal Materials for Length</th>
<th>Non-Ideal Materials for Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sticks – 12” long</td>
<td>Pencils – usable but shorter than sticks</td>
</tr>
<tr>
<td>Pipe Cleaner – 12” long</td>
<td>Spoons – difficult to attach together</td>
</tr>
<tr>
<td>String – As long as needed</td>
<td></td>
</tr>
</tbody>
</table>

*Table 4.* Ideal & Non-Ideal Materials for Key Acquisition.

<table>
<thead>
<tr>
<th>Ideal Materials for Key Acquisition</th>
<th>Non-Ideal Materials for Key Acquisition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnets – Attracted to keys</td>
<td>Clothespin – Difficult to articulate in box</td>
</tr>
<tr>
<td>Paper Clip – Can be bent to hook of small diameter</td>
<td>Tape – Difficult to stick to keys (rough surface). Attracted to side of box (static)</td>
</tr>
<tr>
<td>Pipe Cleaner – Can be bent to hook of small diameter</td>
<td>Spoon – Difficult to impossible to get under keys in narrow box</td>
</tr>
</tbody>
</table>

*Data Collection*
After having spent a few hours in each classroom getting to know the first grade students, each consenting student was solicited for a one-on-one interview with the researcher, author of this study. Each individual interview was videotaped. Interviews took place in a conference room off the main school office. Participants were asked a few warm up questions about their favorite toys and out of school activities to help them become comfortable with the interviewer. Following the questions, participants were presented with the *Trapped Key* task and materials and given the following instructions:

Let me tell you what we are going to do with all this stuff. It’s got two parts to it. It’s got a drawing part and a making part. So, you can see I’ve got some keys trapped in the bottom of this box. Kind of a little dangerous box. It’s got some sharp edges and stuff. So, I want you to see if you can build me something that will get the keys out of the box without putting your hand in too far. And before you build it I’m going to ask you to draw a picture of what you think you are going to make. Alright, so let’s look at all the stuff you’ve got here so you know what you have to work with. You have pipe cleaners, super long sticks, string, obviously scissors so you can cut stuff or do whatever you want with them, all kinds of magnets, tape… And you can use any of these materials any way you want. And if you need help cutting or tying or taping you can ask me for help.

Following this introduction, the task involved the following steps:

a. **Drawing/Planning**: participants were presented with a clipboard to draw the original idea that they were going to try to build.

b. **Clarification**: once they had completed drawing the idea the interviewer asked them to clarify what materials they were using and labeled them on their drawing (i.e., “So this is string here? This is a magnet?”).
c. *Construction of artifact:* participants were given 10 minutes to solve the challenge on their own following the drawing of their idea. Students who were able to construct a solution that retrieved the keys from the box in less than 10 minutes were categorized as having completed the challenge successfully. Students who were unable to create a successful solution in 10 minutes were categorized as incomplete. After 10 minutes had passed, the interviewer intervened with suggestions and helped with constructions so that all children would feel they had been able to retrieve the keys from the box.

**Data Analysis**

The three sources for the data analysis were the drawings the students made before constructing their solutions, their final constructed artifacts, and the video of the interview session. The data analysis looked to quantify and describe the drawing of the planned solution, the final constructed artifact, and the relationship between the two. The analysis of the video focused on how the drawing related to the success of the artifact and the process of creating the artifact. Analysis for the first research question – *How do students’ drawing of their planned solution to an engineering design problem address the problem requirements?* – focused exclusively on the students’ drawings of their planned solutions and how the drawings showed how the students addressed the problem requirements and how their selection of materials accounted for the constraints of the selected materials. The second research question – *What is the relationship between first grade students’ drawing of their planned solution and their constructed artifact?* – analyzed the materials and their position in the drawing of the planned solution with the materials and their position in the constructed artifact (documented in the video) to establish degree of the relationship between the two. Finally, the third research question – *What is the relationship between first grade students’ drawing of their planned solution and their constructed artifact?* – analyzed the materials and their position in the drawing of the planned solution with the materials and their position in the constructed artifact (documented in the video) to establish degree of the relationship between the two.
solution and the success of their constructed artifact? – examines the relationship between students’ drawings of their planned solution and the measures captured from the videotape analysis (task completion, time to completion, number of times artifact tested, and number of unique artifacts constructed).

**Drawing of planned solution and the problem requirements and constraints**

The students’ drawings were analyzed to see how they were able to plan a solution that addressed the engineering design problem requirements and to specifically address the first research question -- *How do students’ drawing of their planned solution to an engineering design problem address the problem requirements?* To do this each drawing was evaluated for whether it addressed conceptual and construction requirements of tool length and key acquisition as well as the constraints related to materials and the box. Length was assessed based on three factors: (1) whether they included a material for length; (2) whether they included sufficient materials to reach the bottom of the box (a single material or combination of materials that would achieve approximately 23 inches – the distance to the bottom of the box); (3) whether the students selected ideal materials for their construction, and specifically which materials they selected (see Appendix A). Similar codes were used for analyzing the key acquisition strategy in the drawing. It was difficult to determine from the drawing whether the quantity of a particular material was sufficient for key retrieval so this category was eliminated from the key acquisition component (see Appendix B).

Students were given a Total Drawing Score (TDS) where the results of the numeric codes achieved for length in drawing (see Appendix A) and for key acquisition (see Appendix B) were added to form a cumulative score rate for how children’s drawing of their planned solution
addressed the problem requirements and the constraints. A maximum score of 8 would represent a drawing where length and key acquisition were addressed with sufficient ideal materials.

Selected examples in Figures 7 and 8 show drawings with high Total Drawing Scores (TDS=8, TDS=6) and those in Figures 9 and 10 show productions with low Total Drawing Scores (TDS=3, TDS=1).

The drawing with Total Drawing Score of 8 in figure 7 addresses length and key acquisition using ideal materials. A stick, pipe cleaner, and string are show for length, which are all ideal materials and easily measure greater than 23” to reach the bottom of the box. The drawing includes a magnet for key acquisition, which is an ideal material.

![Image of drawing with high TDS](image)

**Figure 7.** A student's drawing of their planned solution (TDS= 8).

<table>
<thead>
<tr>
<th>Category</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Addresses LENGTH</td>
<td>1 (Addressed)</td>
</tr>
<tr>
<td>Enough material(s) for LENGTH</td>
<td>2 (Materials able to reach 23” or greater)</td>
</tr>
<tr>
<td>Ideal Materials for LENGTH</td>
<td>2 (All Ideal Materials)</td>
</tr>
<tr>
<td>Addresses Key Acquisition</td>
<td>1 (Addressed)</td>
</tr>
<tr>
<td>Ideal Materials for Key Acquisition</td>
<td>2 (All Ideal Materials)</td>
</tr>
<tr>
<td><strong>TOTAL DRAWING SCORE (TDS)</strong></td>
<td><strong>8</strong></td>
</tr>
</tbody>
</table>

Figure 8 shows a drawing with a Total Drawing Score of 6. This drawing addressed both length and key acquisition. A stick and two pipe cleaners were shown for length (and measure greater than 23”). However, although it included enough materials for length the selected material of tape for key acquisition (tape) was not ideal.
Figure 8. A student's drawing of their planned solution (TDS=6).

Similar to Figure 7, Figure 8 shows a drawing that addresses length and key acquisition. Length is addressed with one stick and two pipe cleaners.
Figure 9. A student's drawing of their planned solution (TDS= 3).

Figure 9 shows a drawing with a lower Total Drawing Score of 3. It was inferred that length was addressed because more than one material was combined. However, the materials were not ideal and measured less than 23 inches. In addition, the spoon selected for key acquisition is not in the ideal material category for this study.

<table>
<thead>
<tr>
<th>Category</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Addresses LENGTH</td>
<td>1 (Addressed)</td>
</tr>
<tr>
<td>Enough material(s) for LENGTH</td>
<td>0 (Materials able to reach 23” or greater)</td>
</tr>
<tr>
<td>Ideal Materials for LENGTH</td>
<td>0 (No Ideal Materials/Unclear)</td>
</tr>
<tr>
<td>Addresses Key Acquisition</td>
<td>1 (Addressed)</td>
</tr>
<tr>
<td>Ideal Materials for Key Acquisition</td>
<td>0 (No Ideal Materials/Unclear)</td>
</tr>
<tr>
<td>TOTAL DRAWING SCORE</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 10. A student's drawing of their planned solution (TDS=1).

Figure 10 shows a drawing that did not seem to clearly address the problem. It was inferred that the selection of a material (pipe cleaner or stick) was meant to reach into the box. However, key acquisition was not addressed and the configuration of the materials would not allow the tool to reach the bottom of the box.
Relationship between drawing of planned solutions and constructed artifact

To establish the relationship between students’ drawings and their constructed artifact a relationship score was calculated by comparing the students’ drawing and their constructed artifact. This relationship directly addressed the second research question – What is the relationship between first grade students’ drawing of their planned solutions and their constructed artifact? The relationship was separated into the two conceptual requirements for the task - length and key acquisition. The analysis focused on comparing the materials, their arrangement, and quantity used for both length and key acquisition in the drawing and artifact. A score of 3 meant that students drew all the same materials in the same configuration and quantity that they used in their final artifact (i.e., perfect match between drawing/plan and construction). A score of 2 meant that there were minor differences. This score was meant to indicate that the students retained their core idea but needed to change the position of the attachment, the material used for the attachment, or realized that they needed an additional quantity of a material they had already selected. A score of 1 was meant to indicate significant differences between the drawing/plan and the construction. This score would indicate that students may have realized the presence of a significant issue with their plan and needed to change the material arrangement or substitute for a new material. A score of 0 was selected when there were no discernable elements of the plan used in the final artifact. The scores (Length Relationship Score [LRS] and Key Acquisition Relationship Score [KARS]) were totaled for each student to generate a total score (see
Table 5).
Table 5. Total Relationship Score – Relationship Between Drawing and Artifact Scores.

<table>
<thead>
<tr>
<th>Length Relationship Score in Drawing and Artifact (LRS)</th>
<th>3 –Identical</th>
<th>2 – Differ in attachment material or different attachment position or increase/decrease of material quantity shown in drawing</th>
<th>1-Differ in material arrangement or additional materials types used</th>
<th>0 – Completely Different</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key Acquisition Relationship Score in Drawing and Artifact (KARS)</td>
<td>3 – Identical</td>
<td>2 – Differ in attachment material or different attachment position or increase/decrease of material quantity shown in drawing</td>
<td>1-Differ in material arrangement or additional materials types used</td>
<td>0 – Completely Different</td>
</tr>
<tr>
<td>Total Relationship Score (TRS)</td>
<td>LRC + KARS</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A score of 6 would represent a drawing/artifact pair where the artifact was identical to the drawing. A score of 0 would represent a drawing/artifact pair where the final artifact looked nothing like the original drawing. Figures 11 through 15 show examples of Total Relationship Scores of 2 through 6 (Pictures were unavailable for TRS scores of 0 and 1).
In Figure 11, which has a Total Relationship Score of 6, the artifact perfectly matches the original drawing in the materials and attachment for length and key acquisition.

Figure 11. A drawing and artifact pair where Total Relationship Score = 6. (LRS=3 KARS=3).
The drawing and artifact are very similar in Figure 12. However, this pair had a Total Relationship Score of 5. The final artifact was connected with tape, which was not represented in the drawing. This addition lowered the Length Relationship Score to 2 (arguably it could have lowered the Key Acquisition Relationship Score but the effect would be the same).

*Figure 12.* A drawing and artifact pair where Total Relationship Score =5. (LRS=2 KARS=3).
Figure 13 has a Total Relationship Score of 4. This pair shows that between the drawing and the artifact the material quantity for length changed (a stick was eliminated) and a material (pipe cleaner) was eliminated. The significant changes to the materials for length yielded a Length Relationship Score of 1. However, the material intended for Key Acquisition (the stick) remained the same, which is why the Key Acquisition Relationship Score remained a “perfect” 3. It should be emphasized that the Total Relationship Score was designed to reflect the relationship between the ideas in the drawing and the artifact. It does not reflect the quality of those ideas.

*Figure 13.* A drawing and artifact pair where Total Relationship Score =4. (LRS=1 KARS=3).
In Figure 14, which has a Total Relationship Score of 3, we see that tape was not shown in the drawing but was added to the artifact to achieve length. The addition of new material types is reflected by a Length Relationship Score of 1. A magnet was shown in the drawing but a greater quantity of magnets was used in the artifact. Additional quantities of a represented material yield a Key Acquisition Score of 2.

Figure 14. A drawing and artifact pair where Total Relationship Score =3. (LRS=1 KARS=2).
Figure 15 has a Total Relationship Score of 2. Tape, not shown in the drawing, was added to the artifact to attach the stick and pipe cleaner, which yielded a Length Relationship Score of 2 for the pair. The material for key acquisition was completely changed from tape to a magnet (attached with paper clips). This total change yielded Key Acquisition Relationship Score of 0.

![Figure 15](image-url)  
*Figure 15. A drawing and artifact pair where Total Relationship Score =2. (LRS=2 KARS=0).*

The total relationship score was only calculated for successful solutions (solutions that retrieved the keys in under 10 minutes) based on the final artifact that was used to retrieve the keys from the box. It was impossible for the incomplete solutions to identify an equivalent artifact that could be used for the comparison as students in this group often had no artifact or a partial artifact at the 10-minute mark.

*Relationship between drawing of planned solution and the success of constructed artifact*

The videos were used to collect information about the students’ process of constructing the artifact. This information combined with the drawing scores was used to address the third
research question – *What is the relationship between first grade students’ drawing of their planned solution and the success of their constructed artifact?* Information collected included:

- Task Completion – Students who constructed a solution to retrieve the keys in 10 minutes or less were categorized as successful. Students who were unable to construct a solution to retrieve the keys were categorized as incomplete.
- Time to Complete Task – For students who created a successful solution, the time was marked from the start of their construction of their artifact (after they had completed their drawing and labeled it with the interviewer) until they extracted the keys from the box with their artifact to generate a “Time to Complete Task.”
- Number of times artifact tested – For each student, every time they put their artifact into the box to attempt to retrieve the keys was counted as a test. The total number of tests was tallied. The total included all tests for all artifacts constructed.
- Number of artifacts constructed – For each student, it was noted each time they began the construction of an artifact. New artifacts were those that were not just the modification (addition, subtraction, or reattachment of materials) of an existing artifact.

**Results**

*General Performance on Trapped Key Task*

A majority of students (77.4%) were able to successfully construct an artifact in less than 10 minutes (Successful) while 22.6% of the students were not able to create an artifact in the designated time (Incomplete). Table 6 shows that the breakdown between genders. Even though boys performed slightly better than girls, Fisher’s exact probability test shows that the difference
was not significant (p=.23). Therefore, in the analysis that follows, data for the two genders are jointly considered.

Table 6. Students’ performance on the Trapped Key Task by gender.

<table>
<thead>
<tr>
<th></th>
<th>Successful Solution</th>
<th>Incomplete Solution</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Females</strong></td>
<td>11 (35.5%)</td>
<td>5 (16.1%)</td>
<td>16</td>
</tr>
<tr>
<td><strong>Males</strong></td>
<td>13 (41.9%)</td>
<td>2 (6.5%)</td>
<td>15</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>24 (77.4%)</td>
<td>7 (22.6%)</td>
<td>31</td>
</tr>
</tbody>
</table>

Figure 16 shows the histogram of times to complete the task (time from start of task to retrieval of keys using artifact). The time for drawing was not included in the time to complete task. All students were given as much time as needed to make their drawing (plan) for the task. The group of students who had a successful solution had a mean time of 3 minutes and 5 seconds with the minimum time being 15.34 seconds and the maximum time being 8 minutes and 54 seconds.
Figure 16. Histogram of completion times for students who were successful at the task (N=24).

The high percentage of students who successfully completed the task (77.4%), combined with a mean completion time (231 seconds) that was less than half of the total time allotted (600 seconds), indicates that, in general, the task may have not been complex enough to significantly differentiated results for this age group strictly based on completion of task or time to complete task. However, there was an interesting range of student outcomes to examine with respect to the three research questions. Figures 17, 18 and 19 show three different approaches to the task. For example, Oscar quickly drew a string with a magnet attached to it (Figure 17). He was able to build the exact same artifact and solved the challenge in 183 seconds.
Figure 17. Oscar's drawing of planned solution and picture of artifact.

Jess carefully drew his solution (Figure 18), which showed a spoon would be used to acquire the keys. He tried his idea but it fell apart during his initial testing. He made some improvements to his design by adding tape and other materials. However, he eventually abandoned his initial idea for a stick and clothespin idea (that involved a slight tilting of the box). He retrieved the keys in 534 seconds.

Figure 18. Jess's drawing of planned solution and picture of artifact.

At the other extreme, Tracy planned a solution with 2 sticks, pipe cleaner, tape and a spoon (Figure 19). She constructed her idea but was unable to get her idea to work. She struggled with attaching the two sticks and getting the spoon to fit into the box. She was not able to create a successful solution to retrieve the keys in the time allowed.
The first research question asked how students’ plans addressed the requirements of an engineering design problem. Analysis of the drawings of the students’ planned solution showed that a majority of the students in both groups included in their drawing some materials for each of the two conceptual requirements (length and key acquisition) of the problem (see Table 7). This indicates that most students understood the conceptual problem requirements and could, in some manner, draw the materials they intended to use to address the requirements.

Table 7. Students’ drawing of materials for addressing length and key acquisition.

<table>
<thead>
<tr>
<th></th>
<th>Successful Solution</th>
<th>Incomplete Solution</th>
<th>Whole Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Addressed length</td>
<td>23 (95.8%)</td>
<td>5 (71.4%)</td>
<td>28 (90.3%)</td>
</tr>
<tr>
<td>Addressed key acquisition</td>
<td>20 (83.3%)</td>
<td>5 (71.4%)</td>
<td>25 (80.6%)</td>
</tr>
</tbody>
</table>
Figure 20 shows two drawings made by students. The left of Figure 20 shows a drawing that displayed materials for length (stick, pipe cleaner and string) as well as a material for key acquisition (magnet). In contrast, the drawing on right of Figure 20 shows a collection of materials but does not specify which materials would be used for length or key acquisition (despite prompts from the interviewer to show how they would be combined).

A majority of students in both groups selected all ideal materials for length in their drawings or a majority of ideal and non-ideal materials for length (see Table 8). However, Fisher’s exact probability test shows the difference was not significant (p=.31) between the successful and incomplete groups. Figure 21 shows two drawings – one that uses all ideal materials and one that uses a combination of ideal and non-ideal materials.
Table 8. Students’ drawing of Ideal Materials for Length.

<table>
<thead>
<tr>
<th></th>
<th>Successful Solution</th>
<th>Incomplete Solution</th>
<th>Whole Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Ideal Materials for Length</td>
<td>18 (75.8%)</td>
<td>3 (42.9%)</td>
<td>21 (67.7%)</td>
</tr>
<tr>
<td>Both Ideal and Non Ideal Materials for Length</td>
<td>3 (12.5%)</td>
<td>2 (28.6%)</td>
<td>5 (16.1%)</td>
</tr>
<tr>
<td>Non-Ideal Materials or No Materials for Length</td>
<td>3 (12.5%)</td>
<td>2 (28.6%)</td>
<td>5 (16.1%)</td>
</tr>
</tbody>
</table>

Figure 21. (Left) Aaron uses all ideal materials (stick and pipe cleaners) for length (RIGHT) Jake uses a combination of ideal (stick) and non-ideal (tape) for length.

The selection of ideal materials indicates that students understood the constraints of the materials and could choose ideal materials to accomplish length. However, the percentages for both the successful and incomplete groups were lower when their drawings were analyzed for whether the
materials they chose were sufficient for length (able to reach the bottom of the 23 inch tall box; see Table 9). Fisher’s exact probability test shows the difference between the successful and incomplete solution groups was not significant (p=.12)

Table 9. Students’ drawing of sufficient materials for length.

<table>
<thead>
<tr>
<th></th>
<th>Successful Solution</th>
<th>Incomplete Solution</th>
<th>Whole Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sufficient Materials for Length</td>
<td>14 (58.3%)</td>
<td>4 (57.1%)</td>
<td>16 (58.1%)</td>
</tr>
<tr>
<td>Partial Materials</td>
<td>9 (37.5%)</td>
<td>1(13.3%)</td>
<td>10 (32.3)%</td>
</tr>
<tr>
<td>No Materials for Length</td>
<td>1 (4.2%)</td>
<td>2 (28.6%)</td>
<td>3 (9.7%)</td>
</tr>
</tbody>
</table>

The Trapped Key task was designed such that no single material would reach the bottom of the box. A majority of students in both groups (58.3% Successful and 57.1% Incomplete) were able to account for the length of the box in their plan by including multiple materials (see example in Figure 22) or materials (string) that could be sized to the appropriate length. Figure 23 shows an example of a drawing that included partial materials for length (a single 12” pipe cleaner).
Figure 22. A drawing that included sufficient materials for length.

Figure 23. A drawing that included partial materials for length.

Figure 23 highlights the fact that while nearly all students understood the conceptual requirement for length, a number of students either did not understand the construction requirement for length.
that highlighted that the tool needed to reach the bottom of the 23” box or did not understand the relationship between the length of the material and the length of the box.

Students’ drawing of ideal materials for key acquisition (see Table 10) illustrated a difference between the students with successful solution and students with incomplete solutions. The majority of students (66.7%) who had successful solutions selected ideal materials for key acquisition. However, none of the students who had incomplete solutions selected ideal materials for key acquisition. Fisher’s exact probability test shows the difference is significant between the two successful and incomplete groups (p=.001).
Table 10. Students’ drawing of materials for key acquisition.

<table>
<thead>
<tr>
<th>All Ideal Materials for Key Acquisition</th>
<th>Successful Solution</th>
<th>Incomplete Solution</th>
<th>Whole Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>16 (66.7%)</td>
<td>0 (0%)</td>
<td>16 (51.6%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Both Ideal &amp; Non-Ideal Materials for Key Acquisition</th>
<th>Successful Solution</th>
<th>Incomplete Solution</th>
<th>Whole Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 (4.2%)</td>
<td>0 (0%)</td>
<td>1 (3.2%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Non Ideal or No Materials for Key Acquisition</th>
<th>Successful Solution</th>
<th>Incomplete Solution</th>
<th>Whole Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7 (29.2%)</td>
<td>7 (100%)</td>
<td>17 (54.8%)</td>
</tr>
</tbody>
</table>

The percentages for successful students selecting ideal materials for key acquisition are also lower than for selecting ideal materials for length 75.8% for length (Table 9) versus 66.7% for key acquisition (Table 10). The range of materials that students included in their drawing is show in Figure 24. There is a high frequency of ideal materials (magnets and pipe cleaners) but non-ideal materials (spoons -to scoop out the keys, string -to hook on to the keys, and tape -to stick to the keys) are also shown. The non-ideal materials are useful for acquiring the keys (or other items) in many situations. However, the tall, narrow, Plexiglas box made positioning a spoon-, string-, and tape-based tools difficult. The selection of non-ideal materials indicates that while most students understood the conceptual requirement of acquiring the keys, some students did not understand or account for the constraints the box dimensions imposed on the materials they selected for key acquisition.
Figure 24. Materials in Drawing for Key Acquisition (Ideal Materials Highlighted in Green Rectangle).

Relationship between drawing of planned solution and constructed artifact

Total Relationship Score Between Drawing and Artifact

The relationship between students’ drawing of their planned solution and their constructed artifact was measured by the how closely the drawing of their planned solution was related with their final artifact calculated using the Total Relationship Score (see Table 5). A Total Relationship Score was only calculated for students with successful solutions. Figure 25 shows the frequency of students by achieved Relationship Scores for successful solutions. The histogram shows that there was a wide range of relationships between plan and final artifact.
The relationship ranged from students who constructed an exact match of their plan (Total Relationship Score=6) to those whose final artifact had little resemblance to their final artifact (Total Relationship Score=1).

Figure 25. Histogram of Total Scores for students with successful solutions.

Grouping the Total Relationship Scores into three categories (see Table 11), we see that over half of the students with successful solutions had a strong relationship (High Total Relationship Score of 4-6) between their drawing and the artifact. This indicates that many students can engage in making most (if not all) of the choices about their solution when planning and also select most (if not all) of the materials they need when planning. It also indicates that students can carry ideas
from the planning to the construction of their artifact. However, 41.7% of the students (Low Total Relationship Scores of 1-3 or No Relationship) did not construct a solution that closely resembled what they planned. This split result raises the question of why students do or do not use their planning ideas in the construction of their artifact.

Table 11. Total Relationship Scores in Groups.

<table>
<thead>
<tr>
<th>Total Score Categories</th>
<th>Number of Students</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Total Relationship Scores (4-6)</td>
<td>14 (58.3%)</td>
</tr>
<tr>
<td>Low Total Relationship Scores (1-3)</td>
<td>9 (37.5 %)</td>
</tr>
<tr>
<td>No Relationship (0)</td>
<td>1 (4.2%)</td>
</tr>
<tr>
<td>Total</td>
<td>24 (100%)</td>
</tr>
</tbody>
</table>

Changing of ideas: Planning quality and drawing artifact relationship

To explore the reasons why students would or would not carry ideas from their drawing to their construction, the relationship between Total Drawing Score and Total Relationship Score was explored (see Figure 26). The hypothesis for this investigation was that students with high Total Drawing Scores, which would indicate they understood the problem requirements and selected ideal materials, would be more likely to use their ideas in the construction of their artifact. However, the results are inconclusive as graph illustrates that there is no clear relationship between the two scores. Similarly Kendall tau-b=-.311 (p=.063) showing a lack of a significant correlation between the two scores. This indicates that other factors may have influenced students to change their ideas from drawing to artifact.
To further explore why students persisted with or changed their ideas from drawing to artifact, the materials used for length and key acquisition were compared between drawing and artifact. Examining the materials used for length between the drawing and the artifact for students with successful solution (see Table 12) there is a slight trend toward students changing
to using more ideal materials. There are three categories of materials that easily achieved length (stick & one or more pipe cleaners, stick & string, and two or more pipe cleaners) that were maintained from drawing to artifact, indicating that students who selected ideal materials for length persisted with their plan for length from drawing to artifact. Students also moved away from materials that were less likely to bring success, such as single non-ideal materials like spoon, tape, and pencil. However, a number of students persisted or changed to materials that were less than ideal for the task (a single stick, pipe cleaner, a combination of non-ideal materials). These solutions often accomplished the task through tilting the box (an interaction with the box that was not explicitly excluded as a potential solution) and multiple trials (brute force persistence). These mixed results make it difficult to draw a single implication about how children changed their ideas from these results. The results do indicate that children adopted different strategies for achieving success – from finding better (ideal) materials for the task to brute force persistence.
Table 12. Materials in Drawing & Artifact for Length in Students with Success for Solutions.

<table>
<thead>
<tr>
<th>Material(s) for Length</th>
<th>Successful – Drawing</th>
<th>Successful – Artifact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Ideal Material (Total)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stick</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>String</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Pipe Cleaner</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Multiple Ideal Materials (Total)</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Stick &amp; one or more pipe cleaners</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Stick &amp; String &amp; Pipe Cleaner</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Stick &amp; String</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Two or more pipe cleaners</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Two or more sticks</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Single Non-Ideal Material (Total)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pencil</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Tape</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Spoon</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Mix of Ideal &amp; Non Ideal Materials (Total)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>One Stick &amp; Tape</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Two sticks &amp; Tape</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Multiple Non-Ideal Materials Total</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Tape, Pencil</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

The graph in Figure 27 shows the materials used for key acquisitions in the drawing and artifact by students with successful solutions. The graph shows that the materials represented in the drawing (in red) and the materials used in the artifact (in blue) for key acquisition. The graph shows that the ideal material of magnets increased from artifact to drawing (indicated by the difference between bars in this category). This indicates that many students changed their original ideas to magnets. However, students didn’t universally change to ideal materials. The ideal material of pipe cleaners decreased from drawing to artifact. This change could be explained by the difficulty first graders might have in molding the pipe cleaners to a hook of the appropriate shape. There is also a decrease drop in some of the non-ideal materials for key acquisition, such as spoons and string. However, there was also an increased use of non-ideal
materials of sticks and clothespins. Similar, to the changes in students’ material use in drawing and artifact for length, these results indicate that students adopted different strategies for success. It was impossible to obtain the keys with a clothespin or stick without tilting the box, which supports the idea that some students opted to alter the box position rather than construct a tool. Similar to changes in materials for length, the lack of a single predictor for why students changed their idea for key acquisition suggests that different students adopted different strategies for achieving success.
Figure 27. Materials Selected for Key Acquisition in Drawing and Artifact by Students with Successful Solutions. The difference between bars in each category indicates change in material use from plan to construction. The asterisks identify ideal materials.

Relationship between drawing of planned solution and the success of constructed artifact

The third research question aimed to investigate whether there was a relationship between the drawing of students’ planned solution and the success of their constructed artifact. Success was examined from multiple perspectives. The first exploration (see Figure 28) looked at whether there was a relationship between completing the challenge and students’ planned solution (Total Drawing Score) and the amount of Redesign they engaged in during construction. Redesign was represented by the Redesign Score, a calculated score based on the number of tests
of the artifact and the number of unique artifacts constructed\(^1\). The Redesign Score was formulated so that a student who created one artifact and tested it one time would have a score of zero, indicating their original idea was highly successful and representative of the fact that they did not engage in redesigning their artifact.

\[
\text{Redesign Score} = \frac{\text{# of unique artifacts created} + \text{# of times artifact(s) tested}}{2} - 1
\]

Figure 28. Graph of All Students with their Total Drawing Score and Redesign Score.

The Total Drawing Scores for both groups of students (those with successful and those with incomplete artifacts) covered a wide range as represented by the blue bars. The highest Total

\(^1\) The following was the basic formula used: \(((\# \text{ of unique artifacts created} + \# \text{ of times artifact(s) tested})/2) - 1\)).
Drawing Scores (8 was the maximum score) are amongst the students who completed successful solutions and the lowest Total Drawing Scores (0 – the minimum score) are amongst the students who had incomplete solutions. However, total drawing scores of 6 appear in both groups. Looking at the Redesign scores, represented by green bars, redesign scores of 0, represented with no green bar, are only presented among the students with successful solutions. The largest redesign scores occurred amongst the students with incomplete successful solutions. While there are potentially interesting trends suggested in the data regarding Total Drawing Scores and Redesign, there is no clear pattern that establishes a relationship between students planned drawing and the success of the solution or the amount of redesign they needed to engage in to make it successful. This supports the results of the previous section that students selected multiple strategies to achieve success and that student characteristics and experience (not measured by this study) may explain what differentiated students with successful solutions from those with incomplete solutions.

To further explore the relationship between success and planning in successful students, the relationship between Total Drawing Scores and Time to Completed Task was examined. It should be noted that students were not instructed to complete the task as quickly as possible to avoid anxiety from fear of failure. However, time to complete task was collected as a rough indicator of how students with successful solutions solved the task. Looking only at the students with successful solutions and their Total Drawing Score (see Figure 29) we see that there is a slight relationship between having accounted for the problem requirements with idea materials (Total Drawing Score) and the time it took to complete the task. This relationship is not particularly strong (R-squared=0.11) nor does it yield a statistically significant correlation (-.331 at the .114 level). This graph did not yield significant insight into what informs the time to
completion of the task but suggests that quality of planning may play a role in how quickly the problem can be completed.

Figure 29. Graph of Time to Complete Task vs. Total Drawing Score.

However, looking at the Time to Complete Task versus Total Relationship Score (see Figure 30) we see a stronger relationship (R-squared=.384) and a significant correlation (-.620 at the .01 level).
Figure 30. Time to Complete Task vs. Total Relationship Score.

Figure 29 and 30 combined indicate that in this study the persistence of a student’s ideas (Total Relationship Score) is a better predictor of time to complete task than the quality of the idea (Total Drawing Score). This yields the conclusion that if you make what you plan you will complete the task more quickly, which means planning has some value in the speed of success.
Discussion

*Drawing of planned solution, problem requirements, and material constraints*

Overall, from examining students’ drawings of their planned solutions, there is evidence that a majority, but not all, of first grade students are able to make plans that in some way addressed the problem requirements and constraints. Over 70% of students (see Table 6), in both groups—i.e., groups with successful as well as incomplete solutions, included one or more material(s) for each of the two conceptual problem requirements (tool length and key acquisition) in their drawing, indicating they understood that their solution needed to include reaching into the box (length) and picking up the keys (key acquisition). As mentioned earlier, this result needs to be taken along with the fact that the task constraints and requirements remained implicit and were never stated explicitly for children. For instance, they were never told explicitly that they needed to address the two requirements of length and key acquisition in order to have a successful solution. They were also never explicitly made aware of the constraints that the materials or box imposed. The result of having the majority of students address the two conceptual problem requirements, result stands in partial contrast to Penner and his colleagues’ work (Penner, Giles, Lehrer, & Schauble, 1997; Penner, Lehrer, & Schauble, 1998) where they found overall that first and second grade students only attended to one of the unstated requirements of building a model elbow (they attended to flexing and not constraining motion). One should keep in mind, however, that the two tasks may be different in terms of the level of difficulty and awareness of the two requirements (elbow movements beyond flexibility in one dimension is not an obvious feature). However, in this study, while over 70% of the students addressed the two conceptual problem requirements of length and key acquisition, a smaller percentage of 58.1% of the students drew materials for length that would reach the
bottom of the 23” box (one of the unstated construction problem requirements). This indicates that nearly half of the students drew materials for length that would not reach the bottom of the box. These results, combined with Penner et al’s results, suggest that design problems that are inclusive for all young children may not be limited in the number of requirements but in the nature of the requirement—meaning that requirements need to be explicit for some students—particularly if they involve more complex ideas of measurement (length of box) or movement. However, these limitations in the nature and explicitness of requirements for engineering design problems are not necessary for all students as is indicated by the 58.1% of students who addressed the issue of the required 23” length in their drawing.

The evaluation of students’ choice of ideal versus non-ideal material for length and key acquisition investigated if students understood the constraints of the materials available for constructing a solution and constraints of the dimensions of the box. A portion of students in both groups was able to select between ideal over non-ideal materials in their plans when considering length. Students were more likely to select ideal materials for length with 75.8% of students with successful solutions and 42.9% of students with incomplete solutions selecting all ideal materials for length (see
Selection of ideal materials generally meant they chose longer materials (stick, pipe cleaner, string) over shorter materials (spoon, pencil).

Examining material selection for key acquisition, 66.7% of students with successful solutions selected ideal materials for key acquisition while none of the students in the group with incomplete solutions selected ideal materials for key acquisition. The difference between material selection for length and key acquisition may be related to the fact that the requirements for a good material for length could be visually assessed (Which material is longer?) while the requirements for a good key acquisition were based on the method the student selected for retrieving the keys and understanding the constraints imposed by the box. For key acquisition, students needed to choose a method for acquiring the keys (e.g., scooping, hooking, attracting them to a magnet) and then select the best materials for the task based on the box and the arrangement of the keys. The complexity of selecting materials for key acquisition may have been a difficulty for some students. In addition, students who selected non-ideal materials for key acquisition may not have fully understood the constraints that the tall, narrow, Plexiglas box placed on the tool’s maneuverability. Many choose plausible materials (tape, string) for key acquisition had the keys not been in such a tall narrow container.

The existing research on children engaged in design also suggests some possible reasons for student’s choice of materials. Fleer (2000b) found that students changed their materials from drawing to construction when they became interested in a material at their table or used by another student. This may have been the case in this study as well in the planning stage as students could see all the materials they were allowed to use. Research in planning in design and technology asserts that students cannot create plans without experience with the materials (Johnsey, 1995; Welch, 1999; Welch & Lim, 2000). While the materials were selected with the
intention of students having prior experience with them, students may have had different levels of experience with them, which may help to explain their ability to choose ideal materials or not. Finally, research in problem solving on children’s planning (William Gardner & Barbara Rogoff, 1990; Gauvain & Rogoff, 1989) indicates that children are able to plan when planning has a benefit to their performance. The *Trapped Key* task required students to plan but there was no consequence to their planning. Hence, some students may not have taken the planning stage seriously and selected materials or ideas that were interesting to them rather than materials they knew would lead to a successful construction.

Relationship between drawing of planned solution and constructed artifact

The second research question focused on how students’ drawing of their planned solution related to their constructed artifact. This question was designed to explore how students’ ideas for a solution persisted from drawing to construction. Previous research in how children’s ideas persist was divided between those who found students’ plans were related to their artifacts (Fleer, 2000b) and those who found that that there was no relationship between plans and the constructed artifact (Rogers & Wallace, 2000). In this study, the results were essentially split, with 58.3% of the students having a high relationship score (their drawings were identical or very similar to their artifact) and 41.7% of the students with a low relationship score or zero relationship score (see Table 11). The results of this study therefore indicate that for a single grade level the artifact drawing-relationship can be different for different students. To explore explanations for the different relationships, the connection between Total Drawing Score and Total Relationship Score (see Figure 26) was explored under the hypothesis that if students had good ideas during the planning those ideas might persist to the construction. However, there was no clear relationship between Total Drawing Score and Total Relationship score, indicating that
addressing problem requirements in the drawing does not necessarily predict that students will use their ideas in construction. This result is interesting as Welch (1999) asserted that planning was unnatural for novice designers because they lacked the knowledge and experience for it to be meaningful. However, this result indicates that for young children, even if students’ plans were likely to succeed (high Total Drawing Score), those ideas may not be fully used in the construction phase – meaning knowledge and experience may not fully explain why planning is not meaningful for novice designers.

To better understand why students ideas may have changed, we looked at how students’ materials changed from drawing to artifact in terms of length and key acquisition. Many students maintained their ideas about using ideal materials and several students changed to using more ideal materials for length (see Table 14). However, students also changed to materials that were non-ideal for the length (i.e. tape). Similarly, for key acquisition, the inclusion of magnets (an ideal material) increased from drawing to artifact, but so did the use of non-ideal materials such as sticks and clothespins. The increased use of ideal materials could be predicted, as we would expect students to move to materials that would help them achieve success. However, the results indicate that students adopted different strategies. It was observed that some students adopted a strategy of altering the environment (tilting the box) or persistence (repeatedly trying a partially sound idea where they might retrieve the keys by luck) rather than making improvements to their artifact by switching to ideal materials. In addition to changing strategies for solving the problem, other possible explanation for the switch to non-ideal materials comes from Fleer (2000b) who observed that students changed their ideas when they actually could interact with the materials they could use for construction. While students could see the materials for the
*Trapped Key* task during drawing, it is possible that materials became more interesting to use when they were able to touch them.

**Relationship between drawing of planned solution and the success of constructed artifact**

The third research question explored whether students’ planning was related to the success of their constructed artifact. The results indicate that there is not a clear relationship between the success of the artifact and the quality of planned solution or redesign of the artifact. The graph of all students’ Total Drawing Scores and Redesign Scores (see Figure 28) shows that students who created a successful artifact and students with incomplete artifacts had a range of Total Drawing Scores. Students in both groups also engaged in redesigning their artifact (i.e., they carried out multiple tests and/or the construction of multiple artifacts). There are some potentially interesting trends - the highest Total Drawing Score was in the group of students with successful solutions while the lowest Total Drawing Score was in the group of students who had incomplete solutions. However, a limitation of the Trapped Key test with respect to planning is that it allowed students to achieve success in ways other than improving the tool (tilting the box or repeated trials of a tool). This makes it difficult to clearly related planning to success because students could make a less than ideal tool work with different strategies.

Time to complete task was collected as a rough measure of the level of success among students who completed the task, although students were not required to solve the problem in the least amount of time possible. There was a slight, but not significant, relationship between Total Drawing Score and Time to Complete Task that indicated faster times were associated with higher drawing scores (see Figure 29). A significant correlation (R=−.620 at the .01 level) was found between Total Relationship Score and Time to Complete Task (see Figure 14). This indicates that the persistence of students’ ideas from drawing to artifact was a better predictor of
how quickly they could solve the challenge than the quality of their planned drawings. This
finding supports the conclusion that students’ ideas can persist from drawing to artifact and that
the persistence of those ideas impacts the speed of solving a design problem. The conclusion
could be drawn that students should persist with their original idea in order to complete the
challenge quickly. However, this conclusion is called into question by case data from within the
incomplete group. Elaine, who was unable to complete the task, tried 13 times to get her original
idea to work. She did not select ideal materials and had trouble keeping her construction
together.

Conclusions and Implications

The purpose of this study was to explore how first grade students’ drawing of their
planned solutions to an engineering design problem related to the engineering design problem
requirements and constraints, the construction of the solution, as well as the success of their
solution. This study yielded 3 major findings:

1) A majority of first grade students can plan a solution on paper that address the
conceptual and construction problem requirements and constraints of an engineering
design problem.

2) Some students struggle with the construction components of the problem
requirements and problem and material constraints.

3) For a majority of first grade students there is a relationship between their
drawing of their planned solution and their artifact.

The first finding is supported by the results of the analysis of students’ drawing related to the
first research question, which examined how students’ drawing addressed the problem
requirements, and the materials selected. The results show that a majority of the students
addressed the conceptual and construction requirements and were able to select the best (ideal) materials in sufficient quantity to meet the requirements within the confines of the constraints of the materials and box. The fact that the majority of first grade students could draw a plan for a solution that addressed conceptual and construction requirements, while keeping in mind the constraints of the problem, supports the inclusion of planning in engineering design activities, curricula, and required learning standards for young children.

The second finding mediates the first by acknowledging that not all children were able to plan on paper a solution that addressed the more subtle construction requirements or accounted for the constraints of the materials and the box. In terms of research, this finding suggests that a greater understanding of the types of problem requirements and constraints that young children can engage in is needed, combined with a more complete understanding of what characteristics and experiences cause certain children to be more successful at planning than others. This finding also has implications for curriculum designers and educators as they think about the structure of engineering design problems for all young children and how to scaffold learning in the classroom. The trouble some students had with some of the requirements suggests that when initially engaging in engineering design problems some students may need to initially work with explicit requirements and that activities and educators need to scaffold students’ experience with implicit requirements.

The third finding demonstrates that there can be a strong relationship between students’ drawing of their planned solution and their constructed artifact. This finding stands in contrast to previous research which asserted that young children could not (Rogers & Wallace, 2000) draw plans for a solution and then construct a related artifact. This study finds that within a population of young children there is a wide range of relationships between students’ drawings of their
planned solutions and their constructed artifact - meaning that some students do build artifacts that are closely related to their drawings and some students do not. This study did not find a single predictor for why some students persisted with ideas from drawing to artifact and some did not. The range of relationships between drawing and artifact among students at a single grade level suggests that characteristics of students and their experiences should be investigated in future research.

This study also sought to understand whether the quality of students’ planning was related to their success. A clear finding about the relationship between the quality of planning and success was not established by the results of this study. The limitations and design of the Trapped Key task may have made this conclusion difficult by not making planning valuable to students in the process of constructing their artifact. Hence, it is possible that some students did not put as much effort into plan or into using their plan to guide their artifact construction.

Research in well-defined problem solving (William Gardner & Barbara Rogoff, 1990; Gauvain & Rogoff, 1989) establishes motivation for students to plan solutions to problems. Future research in this area would need to look at planning in an experimental set-up where students were divided between a control group (allowed to immediately start building a solution) and an experimental group (explicitly required to plan) to see how planning may influence success. In addition, planning would need to have some consequences (only materials shown in the drawing could be used or limited number of trials) to ensure that students were deeply engaged in the planning process. Another complication for establishing the relationship between success and the quality of students planning, is that the quantification of the strength of their drawings of their planned solution (Total Drawing Score) did not include an analysis of how students planned to attach their materials and how they actually attached materials during artifact construction. This
was something the interviewer observed in watching the video as some students struggled with the task. However, it was impossible to quantify from the video and picture the attachment methods and quality of the attachment. This element of the artifact and drawing of the planned solution may help to establish a relationship between planning and success by further differentiating Total Drawing Scores. Future work would need to include more photographs of the students constructed artifact and additional assessment of the artifact during the interview to look at the joining of materials.

An overriding issue with the *Trapped Keys* task was the high percentage of students who completed the task and the relatively low mean time for completion. This may indicate that the *Trapped Keys* task, as an engineering design problem, was not challenging for many students. The small number of students (7) who did not complete the construction of a successful artifact did not allow for statistical significance for correlations or linear modeling. Subsequent research would need a more complex task or more participants to better analyze the relationships in an engineering design task.

This study’s focus on the relationship between the problem requirements, constraints and materials represented in the drawing extends the methodology used to look at planning in design contexts. Previous research on children’s planning in a design context (Fleer, 2000b; Rogers & Wallace, 2000) has looked only at the strength of the relationship between artifact and drawing of the planned solution but have not examined whether students’ drawings demonstrate their understanding of problem requirements or constraints. This study establishes that students’ drawings are a useful component of analyzing children’s planning. This has implications for research in engineering design for children by suggesting that drawings in the engineering design process are a useful and interesting source of information about students’ interpretation of the
problem requirements and their understanding of the materials and constraints. The fact that students were able to illustrate their ideas in a drawing is promising for classroom practice as it allows educators to engage young children in reflecting on their ideas prior to construction.

To date little research has been done that looks specifically at how young children engage in planning solutions to engineering design problems, which have implicit requirements and constraints. This study begins to establish that some young children are capable of planning and implementing solutions that demonstrate their understanding of the implicit requirements and constraints in an engineering design problem. However, the mix of results suggest that some young students may need direct instruction on the steps of the engineering design process that focus on understanding requirements and constraints. While this study established that relationships between students’ drawing and the problem requirements as well as students’ drawing and artifact exist, its unclear the role that the drawing of the planned solution plays – whether it is simply another representation of students’ ideas or whether it actually guides or constrains their artifact construction. More research is needed to establish this to better inform how young children engage in planning and how they can be meaningfully engaged in the planning steps of the engineering design process.
References


APPENDIX A

Coding for Length in Drawing.

<table>
<thead>
<tr>
<th>Addresses LENGTH</th>
<th>1 – Addressed</th>
<th>0 – Not Addressed/Unclear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enough material(s) for LENGTH</td>
<td>2 – Sufficient Materials (2 or more materials that could reach the 23” to the bottom of the box)</td>
<td>1 - Partial Materials (too short)</td>
</tr>
</tbody>
</table>

| Ideal Materials for LENGTH | 2 – All Ideal Materials | 1 – Some Ideal Materials | 0 – No Ideal Materials/Unclear |

<table>
<thead>
<tr>
<th>Material(s) used to achieve LENGTH</th>
<th>0 None/Unknown</th>
<th>1 Magnet</th>
<th>2 Pipe Cleaner</th>
<th>3 Tape</th>
<th>4 Paper Clip</th>
<th>5 Spoon</th>
<th>6 Clothespin</th>
<th>7 String</th>
<th>8 Stick</th>
<th>9 Pencil</th>
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</table>
APPENDIX B

Codes for analyzing key acquisition.

<table>
<thead>
<tr>
<th>Addresses Key Acquisition</th>
<th>1 – Addressed</th>
<th>0 – Not Addressed/Unclear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal Materials for Key Acquisition</td>
<td>2 – All Ideal Materials</td>
<td>1 – Some Ideal Materials</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Material used to achieve Key Acquisition</th>
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