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WISEngineering: Supporting precollege engineering design and mathematical understanding

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A B S T R A C T

Introducing engineering into precollege classroom settings has the potential to facilitate learning of science, technology, engineering, and mathematics (STEM) concepts and to increase interest in STEM careers. Successful engineering design projects in secondary schools require extensive support for both teachers and students. Computer-based learning environments can support both teachers and students to implement and learn from engineering design projects. However, there is a dearth of empirical research on how engineering approaches can augment learning in authentic K-12 settings. This paper presents research on the development and pilot testing of WISEngineering, a new web-based engineering design learning environment. Three middle school units were developed using a knowledge integration learning perspective and a scaffolded, informed engineering approach with the goal of improving understanding of standards-based mathematical concepts and engineering ideas. Seventh grade math students from two teachers in a socioeconomically diverse and low-performing district participated in three WISEngineering units over the course of a semester. Students significantly improved their mathematical scores from pretest to posttest for all three projects and on state standardized tests. Student, teacher, and administrator interviews reveal that WISEngineering projects promoted collaboration, tolerance, and development of pro-social skills among at-risk youth. Results demonstrate that informed engineering design projects facilitated through the WISEngineering computer-based environment can help students learn Common Core mathematical concepts and principles. Additionally, results suggest that WISEngineering projects can be particularly beneficial for at-risk and diverse student populations.

1. Introduction

Increasing exposure to engineering in precollege settings can benefit learning in science and mathematics classrooms. Engineering requires students to apply science, technology, engineering, and mathematics (STEM) concepts to solve complex problems (Katehi, Pearson, & Feder, 2009). Engineering design thinking reflects a mindset of developing innovative solutions by exploring options, testing, and iteratively refining products while considering given specifications and constraints (Dym, Agogino, Frey, & Leifer, 2005). Engineering design activities can help make science and mathematics relevant to students because they are applying classroom knowledge to solve real-life problems, such as designing a garden or developing an insulator for food (Schnittka & Bell, 2011). Thus, engineering design activities hold promise to help students learn STEM concepts in authentic and applied contexts (e.g., Apedoe, Reynolds, Ellefson, & Schunn, 2008; Fortus, Dershimer, Krajcik, Marx, & Mamlok, 2004; Penner, Lehrer, & Schauble, 1998; Puntambekar & Kolodner, 2005). However, a review of existing K-12 engineering education efforts points out the lack of empirical studies on learning outcomes in authentic classrooms and explicitly recommends more research on supporting STEM learning through engineering in precollege settings (Katehi et al., 2009).

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Research also indicates that engineering activities can have little impact on STEM learning at K-12 levels due to a lack of teacher experience and exposure to engineering (Bamberger & Cahill, 2013). Secondary science and mathematics teachers typically have content knowledge of their domain but little experience with engineering. Very few professional development opportunities exist for teachers in engineering education (Katehi et al., 2009). Professional development programs that do exist tend to focus around specific curricula and do not tend to follow best practices in professional development, such as ongoing support during the school year or continuing education (Guskey, 1999). As a result, engineering activities in secondary classrooms emphasize making a final product instead of a design process where constraints focus on tight connections to science and mathematics learning goals.

Computer-based learning environments (CBLE's) can provide needed guidance to incorporate engineering design activities into pre-college settings. Numerous studies demonstrate how computer-based environments can supply targeted support to promote complex learning of science and mathematics (Anderson, Corbett, Koedinger, & Pelletier, 1995; Goldman & Petrosino, 1999; Graesser, McNamara, & VanLehn, 2005; Jacobson & Kozma, 2000; Jonassen & Land, 1999; Lajoie, 2000; Mathan & Koedinger, 2005; Pea, 1985; White & Frederiksen, 2005). However, very few CBLE's have been created to support general engineering design processes (Madhavan, Schroeder, & Xian, 2009).

This paper describes the development and pilot testing of WISEngineering, a new web-based engineering design learning environment. WISEngineering is a free, online learning management system that scaffolds engineering design projects for middle and high school students. WISEngineering builds upon over two decades of technology-enhanced learning research in science through the open-source technologies of the Web-based Inquiry Science Environment (Slotta & Linn, 2009). Instead of scaffolding inquiry projects, WISEngineering supports engineering design projects and provides tools for teachers and researchers to track and assess student understanding. To explore how scaffolding engineering design projects in WISEngineering can impact student understanding of standards-based mathematics concepts, pilot tests of three projects were conducted in seventh-grade mathematics classrooms to answer the following questions:

1. Can scaffolded engineering design projects in WISEngineering help middle school students develop understanding of Common Core mathematical concepts?
2. What kinds of scaffolds benefit various levels of students using engineering design to learn mathematics concepts?

2. Background

2.1. Learning STEM concepts through engineering design

According to the National Academy of Sciences, engineering design can serve as "a meaningful context for learning scientific, mathematical, and technological concepts (Katehi et al., 2009, p. 4). Engineering design is "a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints" (Dym et al., 2005, p. 104). Engineering practices from the Next Generation Science Standards include defining problems, developing models, planning investigations, analyzing data, using mathematics, information technology, or computational thinking, designing solutions, and engaging in argument from practice (National Research Council, 2011).

Research suggests learning STEM content through engineering design holds promise (Daugherty, Reese, & Merrill, 2010). Engineering activities can motivate learning of science and mathematics concepts. Instead of using design activities as capstone projects after instruction, design activities can serve as a context that encourages students to learn relevant STEM concepts by providing real-life and personalized applications of their learning (Hmelo, Holton, & Kolodner, 2000; Kolodner et al., 2003; Roth, 2001). Students are motivated to learn STEM concepts because they can directly apply their understanding to their own design solution. For example, students who may not be interested in solving typical volume and surface area problems may be interested in learning how to make those calculations if they have to design furniture with certain cost and measurement constraints. Supporting students to learn and then transfer their understanding to different contexts can result in more robust understanding of ideas (Bransford, Brown, & Cocking, 2000).

Despite lacking an overall corpus of published research on the impact of teaching engineering design at K-12 levels, a number of programs exhibit the potential of using design activities to teach STEM concepts (Apedoe et al., 2008; Fortus, Dershimer, Krajcik, Marx, & Mamlok, 2004; Penner et al., 1998; Puntambekar & Kolodner, 2005). Many programs demonstrate how engineering design can help students learn science. The *Learning by Design*™ curriculum guides students through cycles of design activities and scientific inquiry (Kolodner et al., 2003). Design projects such as managing erosion of barrier islands and designing lungs showed significant impact on student learning of science concepts (Hmelo et al., 2000). Fortus et al. (2004) developed *Design-Based Science* units that focused on forces with extreme structures, electrochemistry with sustainable batteries, and waves with cellular phones. Middle school students made significant gains on science items from pretest to posttests (Fortus et al., 2004). Silk, Schunn, and Strand Cary (2009) investigated whether engineering design could help student reasoning in high-needs, urban classrooms. Eighth-grade students engaged in designing alarm systems made significant improvement on understanding energy transfer and electrical circuits and outperformed those using similar inquiry or textbook-based lessons (Silk et al., 2009). Penner et al. (1998) engaged students in the modeling of a human elbow to learn biomechanics. By engaging in these design and construction activities as well as guided classroom discussion, students better understood connections between structure and function of the elbow (Penner et al., 1998). Cantrell, Gokhan, and Velasquez-Bryant (2006) created engineering design units with a partnership of middle school teachers and university faculty that focused on concepts such as density, Newton's Laws, and momentum. A comparison of eighth-grade science tests revealed that the engineering units may have helped remedy achievement gaps for certain student populations (Cantrell, Pekcan, Itani, & Velasquez-Bryant, 2006). Design-based approaches may even be more successful than guided inquiry approaches in science (Mehalik, Doppelt, & Schuun, 2008).

Other studies demonstrate how design activities can foster mathematical understanding (McKenna & Agogino, 1998). Burghardt, Hecht, Russo, Lauckhardt, and Hacker (2010) engaged 8th-grade students in a bedroom design project to learn about shapes and scale. Students used Google SketchUp as a computer-aided design (CAD) tool to design and build scale models of rooms with paper and scissors. Students involved in the bedroom design curriculum scored significantly higher on assessments of mathematical concepts than typical students (Burghardt et al., 2010). Similarly, second-grade students participating in a quilt design activity made significant progress understanding transformational geometry and symmetry (Jacobson & Lehrer, 2000). Designing within educational software can impact mathematical understanding in various K-12 settings (Resnick, 1998). For instance, 4th graders at an inner-city public school used a LOGO-based learning environment to learn about fractions through software design. Students demonstrated greater mastery of fraction concepts compared to control classes that followed the traditional mathematics curriculum (Harel & Papert, 1990).

2.2. Difficulties implementing engineering design

Despite the success of these programs, difficulties emerge when implementing engineering design activities in authentic classroom settings. Students do not inherently learn science or mathematics concepts from design activities (Puntambekar & Kolodner, 2005). Many studies demonstrate that students can focus purely on the construction of prototypes without making connections to underlying STEM concepts (Penner, Giles, Lehrer, & Schauble, 1997). Even undergraduate students tend to focus on building structures without engaging in other processes of design or making connections to relevant concepts (Williams, Paretti, Lee, & Gero, 2012). Students can also pick up erroneous ideas from design activities. For example, Penner et al. (1997) guided elementary students through designing a model of a human elbow. Students typically failed to make connections to biomechanics concepts, stating that their own elbows could be bent backwards since their models flexed 360° (Penner et al., 1997).

Teachers' understanding of engineering design also contributes to student difficulties learning from design projects. Most teachers at K-12 levels have expertise in either science or mathematics but not engineering (Ma, 1999). Teachers' superficial understanding of engineering design can lead to superficial student understanding. Instead of instilling engineering design as a systematic, iterative problem solving approach, teachers can reduce design into a procedural and prescriptive sequence of steps (McCormick, 2004). Teachers can also over-emphasize certain aspects of design. For instance, Hynes (2012) found that middle school teachers typically demonstrated a strong understanding of constructing a prototype and redesign while implementing design activities, but low or medium understanding and support for other processes such as researching needs or problems, testing and evaluating, or communicating solutions (Hynes, 2012).

2.3. Scaffolding engineering design

Because of these documented difficulties, successful studies build in substantial scaffolding to help students and teachers implement engineering design activities (Puntambekar & Kolodner, 2005). Scaffolding describes supports that enable learners to perform more advanced activities and engage in more advanced thinking (Vygotsky, 1978). Incorporating scaffolding, either technology-based or non-technology based, into learning environments can greatly enhance student understanding (Bransford et al., 2000). For instance, after initial testing, Penner et al. (1998) introduced support for students to explain and reflect upon their understanding and added guided inquiry activities around biomechanical principles into subsequent studies. The addition of this kind of reflective scaffolding resulted in deeper understanding of scientific concepts (Penner et al., 1998). Precollege engineering education programs typically use text-based methods to scaffold engineering design for students, such as Project Lead the Way (Bottoms & Anthony, 2005) or Engineering is Elementary (Cunningham, 2009).

Scaffolding engineering design processes in a web-based learning environment can help students engage in and learn about engineering design. Technology-enhanced environments provide unique opportunities and affordances to scaffold learning (Guzdial, 1994; Land & Zembal-Saul, 2003; Quintana et al., 2004; Reiser et al., 2001; Sandoval, 2003) and hold promise for engineering education (Bourne, Harris, & Mayadas, 2005). For example, students working on CAD within a computer-based learning environment can share and critique other students' CAD designs and be prompted to reflect upon and refine their designs based on these peer evaluations.

Many studies demonstrate the potential of using technology-enhanced learning environments to support aspects of engineering design in undergraduate settings (Madhavan et al., 2009). Studies have investigated the use of web-based delivery mechanisms for replacement or supplemental instruction (Kirschman & Greenstein, 2002; Paterson, 1999) integrating online supplemental resources into undergraduate engineering courses (Kolar, Sabatini, & Fink, 2002; Marks, 2002; Mohtar & Engel, 2000; Newman & Amir, 2001; Taraban, Anderson, Hayes, & Sharma, 2005) or the use of virtual labs (Candelas et al., 2003; Henson, Fridley, Pollock, & Brahler, 2002; Whitman et al., 2005). Others have explored the use of web-based modules or environments with feedback to help students develop understanding of particular engineering concepts (Bhatt, Tang, Lee, & Krovi, 2009; Rojas, 2002) or solve problem sets (Flori, Koen, & Oglesby, 1996). However, many of these studies were not tied to learning outcomes or had non-significant learning outcomes (Madhavan et al., 2009).

Fewer studies document supporting engineering at the K-12 level. For instance, Fidan, Laurila, and Clougherty (2004) developed a web-based environment to help elementary school students learn the alphabet through an engineering context. Within the engineering alphabet environment, students learned about the profession of engineering, famous engineers, and could take quizzes to verify their learning (Fidan et al., 2004). McKenna and Agogino (1998; 2004) created a web-based instructional module to help students learn about simple machines (SIMALE). Students were able to interact with simulations of various simple machines, record their results in a plotting page, share their findings on a webpage, watch videos describing the design process, and give feedback via an online suggestion box. Pilot testing with middle school summer school students demonstrated that SIMALE helped students make progress on understanding simple machines, but there was no significant difference between the environment and comparable hands-on activities (McKenna & Agogino, 1998; 2004). Cantrell et al. (2006) provided professional development to support teachers to develop technology-enhanced engineering modules. Working together with university faculty, middle school science teachers created design modules that incorporated web-based simulations along with hands-on design activities, instruction, and assessment. Teachers then implemented the modules in their classes over the course of the year. Student learning outcomes favored males as well as non-minorities (Cantrell et al., 2006).

Even fewer studies have investigated general environments to support engineering design in precollege settings. For instance, the STAR-Legacy system scaffolds challenge-based instruction based on the How People Learn framework to support biomedical engineering concepts (Pandy, Petrosino, Austin, & Barr, 2004). Students engage in a cycle including a challenge description, generating ideas, investigating multiple perspectives, research and revision, "testing your mettle" or formative assessments, and then "going public". The STAR-Legacy cycle has been implemented in various undergraduate and high school settings with an overall large effect size (Cordray, Harris, & Klein, 2009). Similarly, the CoMPASS system is a hypertext system that enables deep understanding of science content through concept maps

(Puntambekar & Goldstein, 2007). The CoMPASS system is currently being tested to support deep understanding of science content while students engage in design projects (Puntambekar, 2012).

The WISEngineering system builds upon these efforts to scaffold general engineering design projects and processes explicitly for precollege settings (Fig. 1). WISEngineering features curriculum delivery, assessment, feedback, authoring and research tools based on the open-source Web-based Inquiry Science Environment (WISE) from the University of California, Berkeley (Slotta & Linn, 2009). WISE has been widely used by teachers and students around the world for scaffolding inquiry science and has demonstrated impact on inquiry learning (Linn & Eylon, 2006). WISEngineering extends WISE by transforming the supports for scientific inquiry to facilitate engineering education. WISEngineering prompts students to define problems, identify specifications and constraints, and iteratively develop and refine solutions. In this way, WISEngineering scaffolds engineering practices included in the Next Generation Science Standards (National Research Council, 2011). Prior studies demonstrate the potential of scaffolding engineering activities through WISE (Chiu & Linn, 2011; Cuthbert & Slotta, 2004). However, few, if any, general engineering environments have been used to support mathematics understanding at K-12 levels.

2.4. Supporting informed engineering design

Engineering design processes vary by domain at undergraduate levels (Cross, 2004) as well as individual programs and levels in precollege settings (Fleer, 2000; Roden, 1999; Roth, 1996). Although engineers use a variety of design processes in practice, many K-12 students and teachers have little to no exposure to any form of engineering design. Explicit models of engineering design can help students develop an understanding of the fundamentals of engineering design, similar to principles of cognitive apprenticeship or explicit models of inquiry (Collins, Brown, & Holum, 1991; White & Frederiksen, 2005). Even though there is no "one" engineering design method, generic processes can be extracted and made explicit to provide insight into engineering design, especially in precollege settings (Hynes, 2012).

This study aligns with Dym et al.'s (2005) view of engineering design by using an *informed engineering design* approach for curricular materials (Burghardt & Hacker, 2004). An informed engineering approach emphasizes the intelligent nature of engineering design to help motivate learning of engineering and mathematics concepts in K-12 classrooms. Informed engineering activities ensure that the specifications and constraints target important STEM concepts. For example, a building design challenge can use volume and surface area constraints to motivate learning of volume and surface area concepts. After understanding the problem context, specifications and constraints, students engage in short, focused activities related to the content knowledge needed to develop design solutions. Framing design challenges with special consideration of specifications and constraints helps to focus students on developing relevant STEM concepts or skills instead of uninformed gadgeteering. In contrast, design challenges that only specify materials and give a goal for the strongest bridge or longest flight do not necessarily motivate a deep understanding of statics or aerodynamics. Informed engineering approaches emerged out of many precollege classroom implementations of engineering projects involving hundreds of students (Akins & Burghardt, 2006; Burghardt et al., 2010; Burghardt & Krowles, 2006).

To help students develop understanding of engineering design, each curricular unit used an explicit model of informed engineering design that guides students through the WISEngineering system (Fig. 2). Key processes of the informed engineering cycle are:

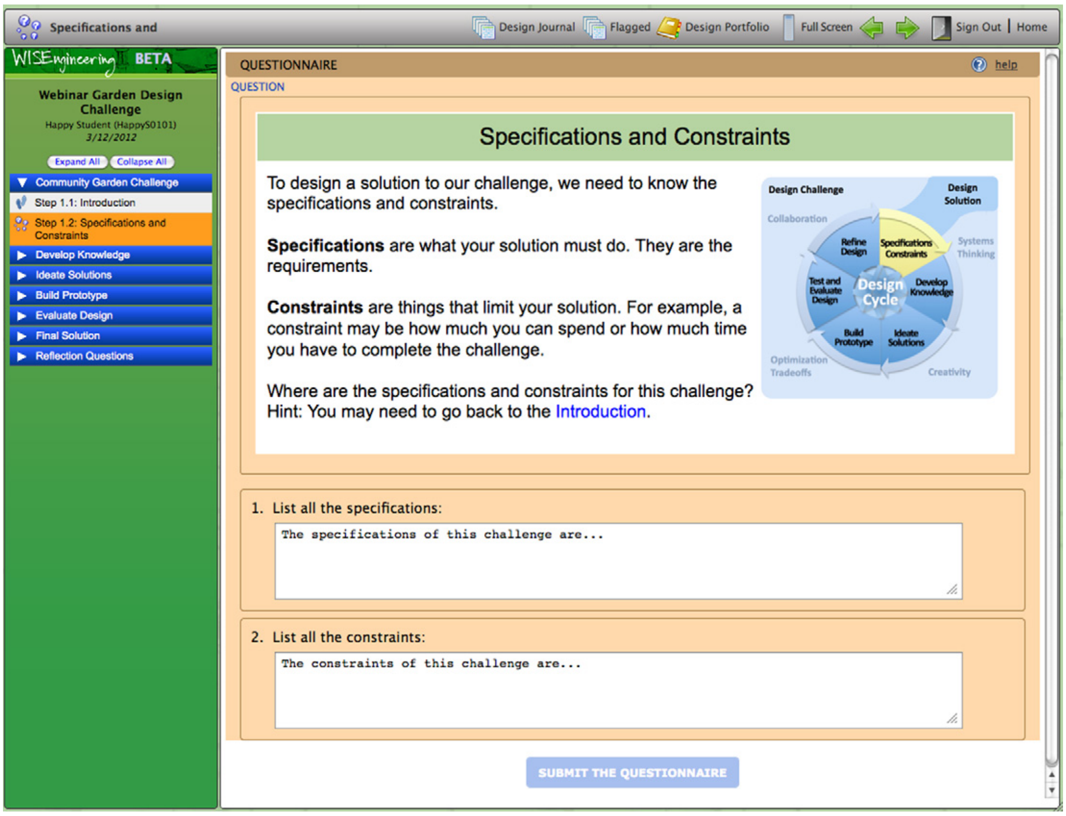

Fig. 1. WISEngineering is a computer-based learning environment that guides students through engineering design projects.

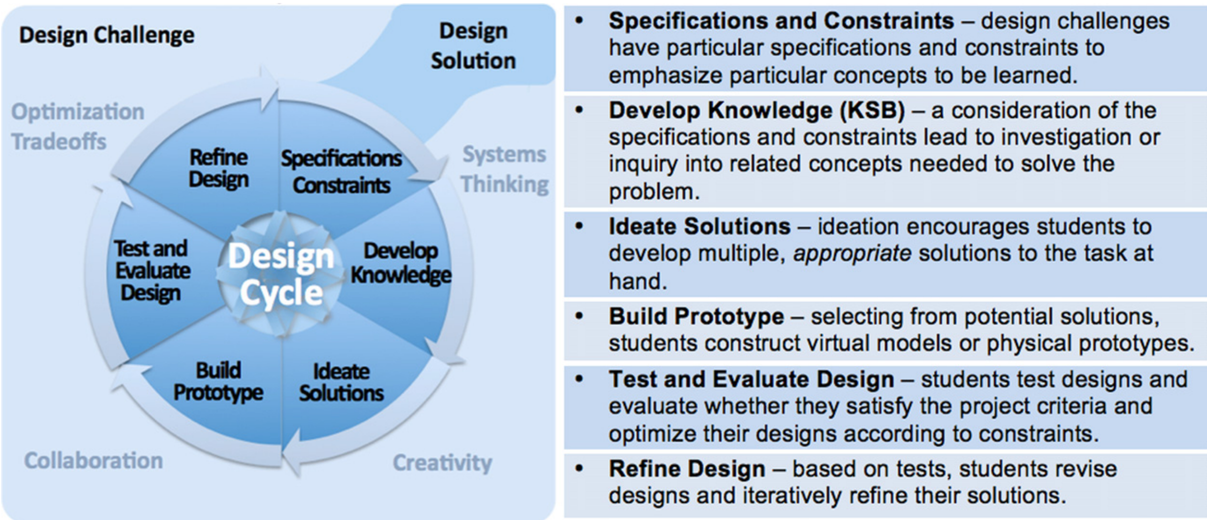

Fig. 2. The informed engineering design model used in WISEngineering projects. The inner cycle represents how these processes are not necessarily stepwise and that design should encompass many iterations and refinements. The outer cycle makes engineering habits of mind such as collaboration and creativity explicit to students.

- *Clarifying design specifications and constraints* – Each design challenge has carefully chosen specifications and constraints for students to consider while developing a solution. Typical constraints emphasized in projects include time or cost. Specifications can emphasize particular concepts to be learned during the project, for instance, certain volume and surface area constraints require students to develop and apply their understandings of these concepts. This process emphasizes that students explicitly recognize and understand constraints and specifications.
- *Develop Knowledge* – A consideration of the specifications and constraints lead to investigation or inquiry into related concepts needed to solve the problem. This process is central to informed engineering design projects; this inquiry is explicitly scaffolded for the students.
- *Ideate Solutions* – After developing knowledge of needed concepts, ideating solutions encourages students to develop *multiple*, *appropriate* solutions to the challenge. Note that informed engineering does not encourage brainstorming, where every idea is welcome and valid. Instead, ideating promotes different solutions that will actually satisfy the challenge.
- *Build Prototype* – Selecting from their potential solutions, this process guides students to construct virtual models or real-life prototypes.
- *Test and Evaluate Design* – After building prototypes, students test their designs and evaluate whether they satisfy the project criteria. This process encourages students to test their own designs as well as share and critique the designs of others.
- *Refine Design* – Based on evaluation and critique results, this process facilitates students to revise their designs and optimize their solutions.

The representation of a wheel with multiple spokes emphasizes the nonlinear aspect of design. Students are encouraged to revisit steps iteratively, for example, going back to specifications and constraints after ideating solutions to choose which design to prototype. The model also includes key engineering habits of mind such as systems thinking, creativity, optimization and collaboration to emphasize their role in the design process.

2.5. Combining knowledge integration with engineering design

By building upon the WISE environment, WISEngineering leverages features designed for knowledge integration (KI; Linn & Eylon, 2011; Slotta & Linn, 2009). KI views learning as building upon and sorting out the numerous, varied, and often conflicting ideas students have about phenomena (Linn, 1995; Linn, Clark, & Slotta, 2003; Linn & Eylon, 2006). Based on decades of research, KI provides principles for curriculum development and assessment constructs that encourage and measure connections students make among ideas (Lee, Linn, Varma, & Liu, 2010; Lee, Liu, & Linn, 2011; Liu, Lee, & Linn, 2011). According to KI, learning occurs when students *elicit* their own existing ideas, *add* ideas from both formal instruction and informal interactions, *distinguish* ideas by developing criteria for their ideas as well as links among ideas, and actively sort out productive from less productive ideas through *reflection* and refinement (Linn & Eylon, 2006).

The KI learning pattern aligns well with engineering design processes (Chiu & Linn, 2011; Linn, 1995). Because of the parallels among informed engineering design and knowledge integration, we leverage the KI learning framework and WISE technologies in WISEngineering to help students learn mathematics through engineering design.

Eliciting ideas enables students to build from their prior knowledge and make connections across contexts and disciplines instead of isolating ideas. WISEngineering uses WISE embedded prompting and assessments to elicit students' existing ideas about the design challenge or related concepts. For instance, students designing a model of a Community Garden are asked to explain their existing ideas about how 2D shapes can fold to 3D objects. In engineering design, students also elicit their ideas by ideating and generating possible solutions to a design problem. WISEngineering leverages WISE drawing functionality to enable students to create initial quick sketches of design solutions based on prior knowledge. For example, students designing gardens use the drawing tool to create initial sketches of plant placement.

Adding ideas through careful instruction aims to help students build upon their existing ideas and make connections to new normative ideas. In engineering design, students need to seek out information and refine their knowledge to design and test their solutions according to specifications and constraints. WISEngineering uses WISE supports to help students add ideas through interactive visualizations and simulations. For example, students designing a community center use web-based interactive visualizations (Annenberg, 2013) to learn about surface area and volume. Students solving a balancing challenge use PhET simulations (Wieman, Adams, Loeblein, & Perkins, 2010) embedded within WISEngineering to add ideas about expressions and equations. Additionally, WISE data tables and graphing technologies were used to help students develop understanding about ratios and proportions.

Crucial to learning through KI is helping students develop criteria and distinguish among their ideas. Eliciting and adding new ideas can result in links and connections among ideas or concepts that may or may not be productive. Instruction that guides learners to evaluate their ideas using powerful criteria is needed to help students learn. When students pick a certain design solution, they need to evaluate their solutions or ideas using design criteria or a set of constraints. WISEngineering uses WISE discussion and navigation features to help students evaluate their designs and ideas. For instance, prompting within WISEngineering guides students to evaluate and comment on the garden designs of other teams. Students are given explicit criteria regarding specifications and constraints and modifications that they use to evaluate their own design as well as the work of their peers.

After learners evaluate their ideas, they need to reflect, refine, and sort out the connections among their ideas. In engineering design projects, after students evaluate designs, students need to reflect upon their tests and evaluations to iteratively refine their solutions. WISE discussion and feedback technologies help students revise and reflect upon their ideas in WISEngineering. WISE technologies can prompt students to use the feedback from peer evaluation to revise their designs and help reflect upon how mathematical concepts may or may not be appropriately used. For instance, after students receive feedback from peers that their garden vegetables are not in the proper ratio, students are guided to refine their understanding of ratios and proportions in the context of their vegetable design.

2.6. WISEngineering features that support informed engineering design

In addition to existing WISE functionalities, particular features were designed for the WISEngineering environment to support informed engineering design, namely, design cycle navigation, the digital design journal, Design Portfolio, and the Design Wall. External technologies such as digital fabrication were also added to WISEngineering projects to facilitate iterative prototyping for students. The following sections describe these features in more detail.

2.6.1. Design cycle navigation

Students navigate through WISEngineering projects by progressing through an explicit engineering design cycle. The design cycle navigation identifies students' locations within design projects. For example, if students are currently clarifying specifications and constraints, or developing knowledge, that step is highlighted in the design cycle map. Each overall process is then broken down into discrete steps on the left-hand side of the screen (see Fig. 1). Students are free to choose to go back to certain phases of the process at any time during the project, yet the linear structure on the left guides students general progression throughout the design challenge.

2.6.2. The Design Journal

Student work in the Design Journal is composed of all of the written responses, drawings, diagrams, or designs that student produce in any of the other steps within WISEngineering. For example, in Fig. 3, a student has summarized the introductory material for the Community Garden activity. The student has listed the area specifications, as well as the needed vegetables and the constraints on money and time that are laid out in the unit. Prompts throughout WISEngineering projects ask for this kind of reflective analysis from students. Students who respond to these prompts will automatically end WISEngineering projects with a Design Journal that provides a complete record of their own design efforts. Other WISEngineering steps incorporate drawings or screenshots. These are automatically pulled into the Design Journal as well, and students can subsequently transfer these into their Design Portfolios. Students will automatically end WISEngineering projects with a Design Journal that provides a complete record of their design efforts.

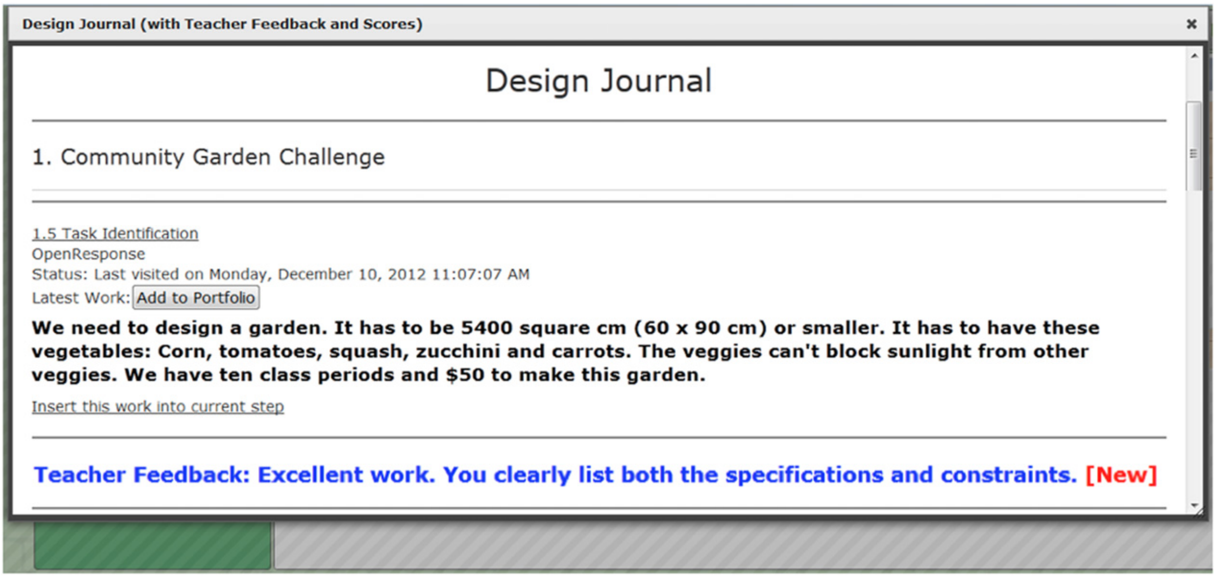

Fig. 3. This screenshot shows work that automatically transferred from students' work in step 1.5 of the activity. At the bottom of the screen, the text of the teachers' response is shown in blue text, with a red notification indicating that the teacher feedback is new. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Teachers can annotate, comment, or grade student work in the Design Journal to guide student progression through a project. Fig. 3 also includes a teacher response to student work that reinforces the student's efforts. After a teacher has provided this kind of response for a student, the student is provided with an automatic alert upon re-entering the project. Thus the teacher can maintain two-way communication with all the students from one central location.

2.6.3. The Design Portfolio

Either during a design challenge or after a project is completed, students select specific artifacts from their Design Journals to share with teachers and peers. This selected work forms a Design Portfolio, enabling students to reflect upon, revise, and share their work. Students can annotate or comment on their selected artifacts and reorder or rename steps or pieces of work. For example, in Fig. 4, a student has transferred text from the Task Identification step (also shown in Fig. 3). The Portfolio only includes the highlighted artifacts and solutions, such as the sketch that this student has created in WISEngineering in subsequent step 5.1. This student has added a comment on the shortcoming of this design. It does not meet the constraint that vegetables cannot overshadow other vegetables in the garden.

The process of reviewing one's Design Journal is intended to promote reflection on students' design processes. Sharing and presenting Design Portfolios are meant to spark class discussion and collaboration, as well as facilitate the distinguishing of ideas.

2.6.4. The Design Wall

Students benefit from sharing and critiquing one another's designs. The Design Wall is a discussion tool with image embedding and comment capability patterned after familiar social network website functionality. Students can respond to one another's ideas about designs and refine their own ideas or designs. Each class has their own Design Wall, so all students in the class will see all design postings by other students. In WISEngineering projects, students are guided to post, reflect, and critique one another's designs (Fig. 5). The Design Wall encourages the knowledge integration processes of evaluating and refining ideas by enabling peer critique of their designs.

2.6.5. Digital fabrication

Digital fabrication is the design and creation of physical objects from a digital device (Bull & Garofalo, 2009; Chiu, Bull, Berry, & Kjellstrom, 2013). Commercially available devices such as two-dimensional die-cutters and three-dimensional printers are currently accessible in educational settings. Two out of the three units in WISEngineering described here used 2-D digital fabrication technologies. Students used simplified CAD programs to develop three-dimensional designs. These designs were first printed using a standard inkjet printer on sheets of cardstock and next sliced into proper shapes and perforated for folding with two-dimensional die-cutter machines. Students then folded and assembled the paper into three-dimensional designs.

3. Methods

3.1. WISEngineering curricular units

The three units piloted in this study include *Community Center Challenge*, *Community Garden Challenge,* and the *Balancing Act* projects. Learning goals for each unit focused on specific mathematics concepts outlined in the Common Core State Standards for Mathematics (Common Core State Standards Initiative, 2012). Each unit was piloted before implementation with small focus groups, and revisions

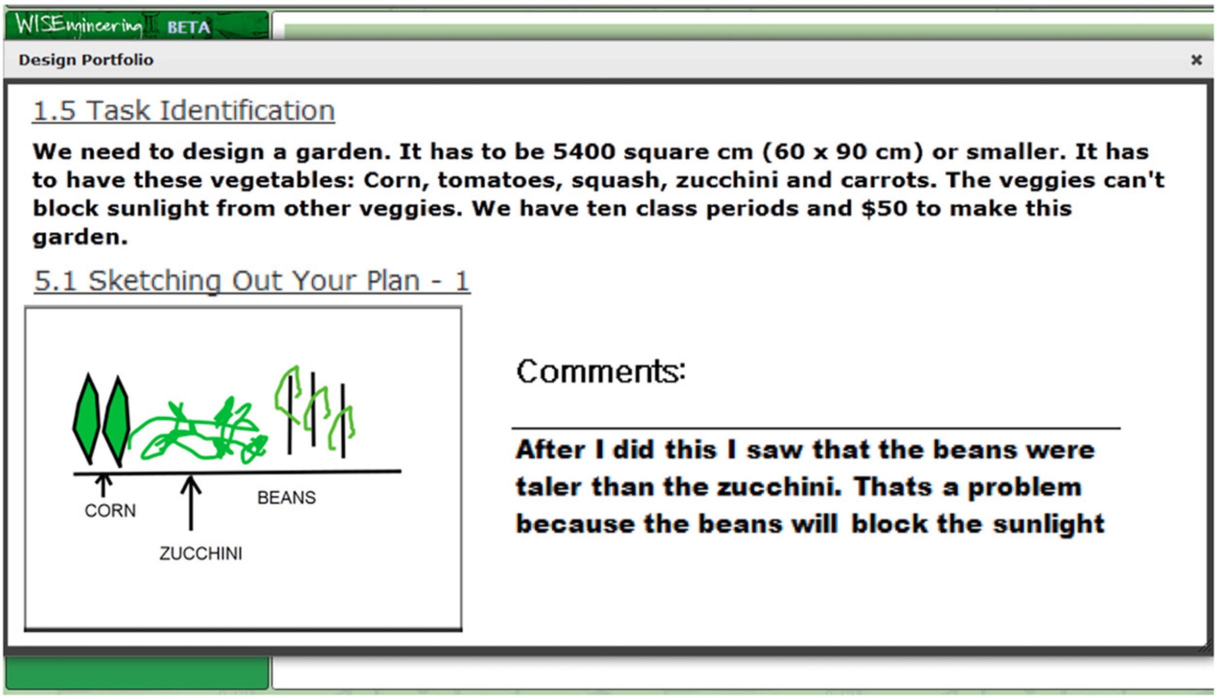

Fig. 4. The Design Portfolio is a streamlined version of the Design Journal, with space for students to reflect on their own work. This page includes two items that a student has transferred from the Design Journal, as well as a student reflection on a sketch.

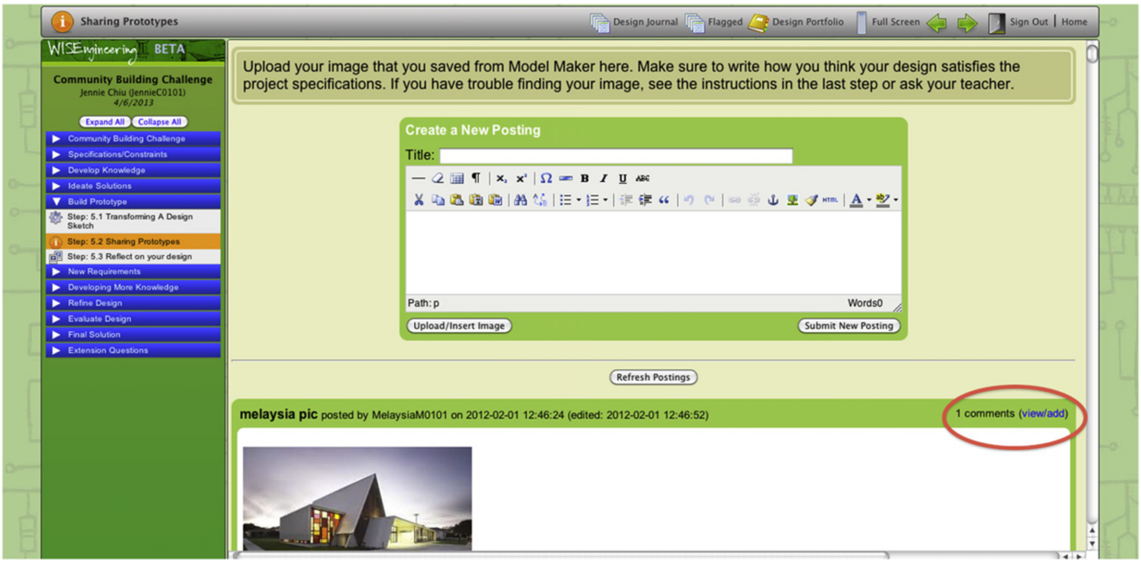

Fig. 5. The Design Wall enables students to collaborate by sharing and critiquing designs. The WISEngineering interface also features links to students' Design Journals and Design Portfolios at the top-right corner. The view/add comments button, shown circled in red (added here for emphasis) allows a student to respond to another student. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

focused around encouraging knowledge integration and informed engineering design. A range of pilot activities were used to investigate what types of WISEngineering units could be successful in low-performing mathematics classrooms.

The Community Center Challenge (CC) focused on using knowledge of volume and surface area of shapes to design community centers. Students learned how to calculate area, volume, and to understand spatial reasoning as they plan, design and build a paper model of a community center. The design specifications related to the cost of the centers, which was in turn proportional to volume and surface area the students could design. CC used the Design Wall to elicit and ideate ideas by having students find and post pictures of community centers. Students were prompted at the beginning of the project to click on the Design Journal and then reminded to add or refine their Journal throughout the project. Students used dynamic visualizations to add ideas about volume and surface area (Annenberg, 2013) and drawing tools to sketch their initial design ideas. Embedded assessments throughout the unit aimed to help students make connections among the targeted mathematic concepts and their designs. Students used CAD tools and die-cutters to digitally fabricate their center designs during the unit and then posted their CAD designs for peer evaluation using the Design Wall. At the end of the project, students were asked to select what they would like to share from their Journals into the Design Portfolios and then share their portfolio with one other group. The unit was designed to last for two weeks.

The second unit, Community Garden Challenge (CG), centered on the design of a garden to maximize vegetable output, where cost, along with the ratios of the heights of plants, served as specifications and constraints. This unit included mathematics concepts that focused on unit price, unit rate of change, and proportions. Students planned, designed, and created a paper model (pop-up) of a Community Garden that includes different types of vegetables – all of different heights and of different costs. Students were prompted at the beginning of the project to explore the Design Journal and to add and refine their Journals throughout the project. Numerous embedded activities reinforced Common Core mathematics concepts of ratio and proportion and required users to make choices on how to allocate money and gardening space. These activities included creating tables with immediate feedback on the correctness of their calculations and embedded assessments emphasizing graphical understanding of proportion. Students used digital fabrication and CAD tools to create simple pop-up designs of the kinds of plants and plant arrangements in their community gardens. Students were guided to post their designs for evaluation on the Design Wall and then evaluated one other student group's design given explicit design criteria. Unlike CC, CGC did not explicitly ask students to create and share a Design Portfolio at the end of the project. CG was also designed to last for two weeks.

The third unit, Balancing Act (BA), challenged students to devise a solution to balance someone on a seesaw while developing understanding of expressions and equations. BA guided students to devise, test, and iterate a virtual solution using a PhET simulation (Wieman et al., 2010) and learn algebra related skills, such as solving for x in simple equations. Students used the simulation and embedded prompts to elicit initial ideas on how to get the see-saw to balance. Curriculum pages within WISEngineering added ideas about mathematical expressions to balance the beam. Students revisited the simulations to test their new understanding of equations and created and explained their design solutions using drawing and embedded assessment tools. BA was designed to last only 90 min and did not use digital fabrication or CAD technologies. Because of the very short and focused nature of the project, the unit did not use any Design Wall steps. The Design Journal was available for the students to use but the unit did not explicitly mention or guide the students to use either the Journal or the Portfolio.

3.2. Participants

Seventh graders in general mathematics classes from two schools participated in this study. Students attended two of the lowest performing schools in a district currently under state takeover. Both schools had a greater proportion of students classified as partially proficient in mathematics (School 1: 52.9%, School 2: 75.4%) and language arts/literacy (School 1: 67.6%, School 2: 82.8%) compared to state averages (Math: 34%, LAL: 36.3%). Both schools also had a small proportion of students classified as advanced proficient in math (School 1: 10.6%, School 2: 1.6%), and language arts/literacy (School 1: 2.2%, School 2: 0%), compared to the state (Math: 24.4%, LAL: 12.4%). Many students at both schools were eligible for individualized education plans (School 1: 12.6%, School 2: 15.3%), and/or classified as having Limited English Proficiency (School 1: 28.6%, School 2: 9.3%). School 2 also had a higher rate of suspensions (24% of students suspended during academic year) than the district (16%) or state (4%).

Two teachers involved with the project chose two of their mathematics classes to use WISEngineering units as replacement curricula. Participating teachers attended two days of professional development that provided instructional demonstrations for the use of digital fabrication technologies as well as the WISEngineering system.

3.3. Intervention

Students used WISEngineering as replacement curricula in the mathematics classrooms. Pretests and posttests administered before intervention and after completion were used to study changes in student math content knowledge. Students from the same schools and teachers ($n = 26$) were used as a comparison sample and solved several of the same posttest questions at the end of the school year. Comparison students received typical instruction in all related content areas. All students took mandatory state standardized tests both before and after all of the WISEngineering modules. A random selection of comparable students were selected from the district to compare WISEngineering student performance on state standardized tests to other students in the district.

3.4. Data sources

Standards-based mathematics pretests and posttests developed by the research team were administered with pencil and paper to individual students before and after implementation of each unit. Pretests and posttests were developed through an iterative process that involved review of the lesson, consultation with the lesson author, collection of existing assessment items following a review of state standardized tests, textbooks, and other resources, try-out with middle school students, and revision. Student performance on state standardized mathematics tests was collected for both WISEngineering and a random sample of students from the same district. The research team also conducted semi-structured student and teacher interviews after each unit implementation to investigate attitudes toward engineering and the WISEngineering units. The following section describes the content assessments in more detail.

3.4.1. Community center assessment

The Community Center pretest and posttest assessments included nine questions about area, volume, surface area, nets/spatial reasoning, and specifications and constraints. Seven of the questions were multiple-choice and two were open-ended. One of the open-ended questions contained three parts; the other question contained two parts. Topics included two questions on surface area, three questions on volume, three questions on nets/spatial reasoning, and one question on specifications and constraints. Each part of the open-ended questions were scored separately.

3.4.2. Community Garden assessment

The Community Garden pretest and posttest assessments consisted of thirteen questions about unit price/rate of change, and proportions. Nine of the thirteen questions were multiple choice and the remaining questions were open ended. Five of the questions addressed unit price/rate of change, seven questions addressed students' knowledge of ratios and proportions, and one question examined whether students could use their knowledge of ratios and proportions to find the best deal on clothing. One of the open-ended questions about unit price required students to find the unit price of goods at two competing businesses and to graph the data.

3.4.3. Balancing Act assessment

The Balancing Act pretest and posttest assessment consisted of five questions. One question asked students to provide two examples of levers that they had seen in real life. Four questions presented students with scenarios where they either had to balance a lever or a see-saw by solving equations or determine if a lever or see-saw was already balanced. In order to balance the lever or see-saw, students had to determine either where to place a mass on the lever, or the mass needed to balance the lever.

3.5. Data analysis

Each pretest and posttest question was scored as correct (1) or incorrect (0). An aggregate score was computed for each student based on the percentage of items correctly answered. Partial credit, scored as 0.5, was awarded on questions about specifications and constraints. The percentage correct score was computed for each pre- and post-assessment. These aggregate scores were then used for subsequent analyses. If a student skipped an individual question but answered others, the skipped question was treated as an incorrect answer. If a student left three or fewer questions blank, these questions were marked as incorrect. Students who did not complete both a pre and post-test and students who skipped four or more questions were omitted from this analysis.

Student performance on standardized state mathematics tests was used to classify students into partially proficient, proficient, and advanced proficient categories. These categories were used to investigate differences for WISEngineering units among students with different levels of prior mathematics understanding according to state testing, as well as investigate performance on state testing after implementing WISEngineering. Paired sample t-tests were used to explore performance differences from pretests to posttests. Effect sizes were calculated using pooled standard deviation (Cohen, 1988). Semi-structured student and teacher interviews were used to supplement quantitative results. Missing data due to absenteeism were dropped from analysis.

4. Results

4.1. Implementation results

Both participating teachers implemented the units in their classes. A researcher was present during the first week of CC to help with technical difficulties from the digital fabricators or software needs. Otherwise, researchers only observed classrooms during subsequent runs and to help with the first week of CC and facilitate assessments.

Logistical difficulties arose throughout the CC implementation. Challenges included getting access to computer labs with the district requirements for online testing of all students multiple times during the school year (partially in response to their state takeover status). Students huddled around laptops to work in WISEngineering and were provided a binder of similar paper-based activities when computers were not available. CC became a hybrid online and paper-based project that lasted 5 weeks. During this time, numerous days were also spent on non-WISEngineering tasks. Difficulties with the digital fabricators resulted in around half of the students cutting their designs out by hand. However, all students were able to use the CAD programs to design their own community building. Students worked through the units in groups of 2–4 chosen by the teachers to facilitate collaboration.

For CG, teachers were better able to access computer labs, and all students completed the garden design challenge in WISEngineering. Students completed CG in three weeks without any major technical difficulties, using both CAD and digital fabrication. Again, students worked through the units in pairs chosen by the teachers. Students completed BA in one 90-min class period and worked individually at the computers. Logistical issues and teacher illness contributed to a reduction in student participation; this is particularly true regarding the Balancing Act unit.

4.2. Student learning outcomes

4.2.1. Community center outcomes

For the Community Center Challenge, students using WISEngineering demonstrated significant overall gains in mathematics knowledge from pretest to posttest assessments, with a large effect size ($t(79) = 7.61$, $p < 0.05$; $d = 0.92$). Proficiency level had a significant effect on posttest score [$F(2,79) = 28.35$, $p < 0.01$]. Tukey HSD post hoc comparisons indicated all three levels significantly differed from each other (Table 1). CC had a large effect on students labeled as advanced proficient ($d = 1.91$) and proficient ($d = 1.40$) by state testing and a medium effect on partially proficient students ($d = 0.42$).

The visualizations and instruction used within CC may have contributed to these trends across proficiency levels. As part of the developing knowledge steps, students went to external websites with visualizations and activities that emphasized pattern finding among shapes. These visualizations and problems may have especially benefitted more advanced students. Additionally, the feedback and problem-solving pertaining to surface area and volume was also provided through an external website, thus, although the website provided feedback on students' answers and guided students through problems, there was no explicit, step-by-step instruction and feedback. Partially proficient students may not have benefitted as much from the more self-guided development of knowledge.

4.2.2. Community Garden outcomes

Overall, student scores significantly increased from pretest to posttest on CG ($t(65) = 6.29$, $p < 0.01$; Table 2). Proficiency level had a significant effect on posttest score [$F(2,63) = 21.91$, $p < 0.01$]. Tukey HSD post hoc comparisons indicated all three levels significantly differed from each other (Table 2). Contrary to CC, students labeled as partially proficient by state testing had the largest gains from pretest to posttest ($d = 1.38$). CG also had a large effect on students labeled as proficient ($d = 0.84$), however, CG had a small effect on advanced proficient students ($d = 0.30$).

In CG, explicit, step-by-step instruction was provided with feedback within WISEngineering steps. For example, students had to calculate and fill out tables to determine cost per yield for specific vegetables with different vendors and received specific feedback if their calculations were incorrect. Additionally, students were required to look at graphical representations of the data to determine trends graphically. Highly scaffolded instruction may have benefitted partially proficient and proficient students, whereas advanced proficient students may not have benefitted as much from this kind of explicit instruction.

4.2.3. Balancing Act outcomes

Overall, students exhibited significant improvement on BA questions from pretest to posttest ($t(35) = 8.72$, $p < 0.01$, $d = 1.76$). Proficiency level had a significant effect on posttest score [$F(2,33) = 4.30$, $p < 0.05$]. Tukey HSD post hoc comparisons indicate the mean score for the partially proficient group was significantly different than the proficient and advanced proficient groups, but there was no significant difference between the proficient and advanced proficient groups (Table 3). Students in all three levels of math proficiency had large effect sizes. These outcomes are in large part due to students' low performance on the pretest assessments. To answer correctly, students needed to know specific torque concepts and be able to solve complex two-step equations. Nearly seventy percent of the students did not receive full credit for any question on the pretest. However, at the end of the 90-min lesson, students were able to successfully solve some these

Table 1
Means, standard deviations, and effect sizes for CC pretest and posttests by proficiency level.

Group	Pretest (% correct)		Posttest (% correct)		Effect size
	Mean	Standard deviation	Mean	Standard deviation	
Overall sample ($n = 80$)	47.14	17.57	66.71	24.13	0.92
Partially proficient ($n = 21$)	35.32	16.11	43.45	21.37	0.42
Proficient ($n = 50$)	48.19	14.64	71.44	18.15	1.40
Advanced proficient ($n = 9$)	68.93	13.40	94.68	12.31	1.91

Table 2
Mean, standard deviation and effect size for Community Garden pretests and posttests by proficiency level.

Group	Pretest (% correct)		Posttest (% correct)		Effect size
	Mean	Standard deviation	Mean	Standard deviation	
Overall sample ($n = 66$)	45.09	20.49	57.39	14.79	0.68
Partially proficient ($n = 13$)	25.05	12.30	43.29	13.28	1.38
Proficient ($n = 45$)	45.63	17.09	57.89	11.22	0.84
Advanced proficient ($n = 8$)	74.60	7.75	77.5	10.17	0.30

complex multi-step problems. In particular, results suggest that proficient and advanced proficient were able to grasp the concepts in the short amount of time, but the partially proficient students may have needed additional support.

4.2.4. Comparison to Non-WISEngineering students

Comparison students from the same schools and teachers ($n = 26$) were given an assessment that included 14 mathematics content knowledge questions selected from each of the three WISEngineering individual lesson assessments. The comparison assessment was given after the WISEngineering students completed all three units. A summed score was computed for WISEngineering students using just those items that were shared by both WISEngineering and comparison groups. WISEngineering students ($M(SD)$: 54.13(20.44); $n = 92$) outperformed comparison students ($M(SD)$: 43.63(24.92); $n = 26$), a difference that was statistically significant ($t(116) = 2.20$, $p < 0.05$). Comparison students were similar in proficiency distribution, with 65% of students in the comparison group and 64% of the WISEngineering students classified as partially proficient.

4.2.5. Student performance on state standardized tests

Students in participating schools were required to take a standardized computer adaptive assessment to capture the growth of individual students and entire classes. The test has been validated with representative national samples and scores range from 0 to 1400, calculated based on the difficulty of the questions and number of correct responses. To determine whether students who participated in WISEngineering did better on the standardized test at the end of the year than other students in the district, an independent samples *t*-test was conducted with WISEngineering students and a comparison sample of students randomly selected from the district. On average, students who participated in WISEngineering ($M(SD) = 835.68(104.40)$; $n = 61$) significantly outperformed the comparison sample ($M(SD) = 759.17(126.04)$; $n = 60$), $t(119) = 3.64$, ($p < 0.001$).

A matched pairs *t*-test was used to determine if there was statistically significant growth for WISEngineering on the STAR exam from the initial fall administration to the final spring administration based on proficiency levels. Students who participated in WISEngineering improved their scores by nearly 63 points from fall ($M(SD)$: 803.37(83.82)) to spring ($M(SD) = 865.91(76.89)$), compared to an average of 26 point growth over the same period for the comparison sample. Even though the sample size was small for partially proficient and advanced proficient groups, all groups exhibited statistically significant positive growth with large effect sizes (Table 4).

4.3. Affective student outcomes

4.3.1. Promoting collaboration

Classroom observations and teacher and student interviews revealed that the WISEngineering projects promoted collaboration, tolerance, and development of pro-social skills among many at-risk youth. When debriefing the social worker who provided support at one school, she made comments referring to WISEngineering as "amazing," noting that "students who are typically disengaged in school wanted to be there" and "students who I see privately who have difficulties getting along with others are now working with their peers." By challenging students in design tasks requiring thought, creativity, and collaboration, the students were authentically motivated and engaged in math class.

At the conclusion of the three lessons, students were asked how much they enjoyed working with their peers to complete the design challenges. Over 80% of the students wrote that they enjoyed engaging with the design challenge through group work. Students found that working in groups helped them to form closer friendships (e.g., "Because it brings me closer to classmates like friend and not just some kid in my class"), complete the work more quickly (e.g., "Working with others shows teamwork also gets everything done quicker"), develop a support system (e.g., "I liked working with the other students because whenever I fell behind they would always help me and of course I'd return the favor"), learn new ways to work with others (e.g., "Because it taught me how to work well with others and how we can put our heads together"), and seeing the work from multiple perspectives (e.g., "We had our own design ideas and when we put them together it made something really cool and creative").

Fewer than 20% reported that they did not enjoy working with other students on the design challenge. These students appeared to find it difficult to compromise with other students (e.g., "they don't do what I want them to do"), deal with group members at different levels

Table 3
Means, standard deviations and effect sizes for Balancing Act pretest and posttests by proficiency level.

Group	Pretest (% correct)		Posttest (% correct)		Effect size
	Mean	Standard deviation	Mean	Standard deviation	
Overall sample ($n = 36$)	12.96	14.01	53.24	29.23	1.76
Partially proficient ($n = 4$)	8.33	9.63	27.08	18.48	0.90
Proficient ($n = 23$)	13.04	14.83	57.25	28.13	1.97
Advanced proficient ($n = 6$)	16.67	17.48	69.44	29.19	1.95

Note: *N* from overall sample includes students who did not have state standardized test scores, and therefore, could not be classified into proficiency level groups.

Table 4
Means, standard deviations and effect sizes for standardized test performance by proficiency level.

Group	Fall scaled score		Spring scaled score		Effect size
	Mean	Standard deviation	Mean	Standard deviation	
Overall sample ($n = 43$)	803.37	83.82	865.91	76.89	0.78
Partially proficient ($n = 7$)	727.43	36.93	791.57	37.93	1.71
Proficient ($n = 27$)	796.11	64.44	857.56	50.98	1.06
Advanced proficient ($n = 6$)	936.33	68.28	997.33	61.01	0.94

Note: *N* from overall sample includes students who did not have state standardized test scores, and therefore, could not be classified into proficiency level groups.

(e.g., "some people would be far behind and holding me back"), engage all group members in the work (e.g., "my team expected me to do most of the academic work"), or keep all group members on task (e.g., "I didn't enjoy working with others because they'd play around"), or simply found working in groups confusing (e.g., "they made it confusing").

4.3.2. Student attitudes about learning mathematics through WISEngineering

Although the design tasks required the learning and application of standards-based mathematics, science concepts, and relevant STEM habits of mind, the students overwhelmingly reported they were very engaged, and that they liked the opportunity to be creative and challenged. When asked about how WISEngineering was different from other math classes, a large number of responses described how the type and longevity of the teamwork activities that students encountered in WISEngineering was preferable compared to a typical math class. Students reported that WISEngineering activities were more applied and less based upon solely formulaic problem solving. (e.g., "I noticed it was different because the project was very challenging and work with others help understand more," "It was different because we worked on something other than doing work in the textbook or in the workbook," "The difference was that they can tell us about their ideas on how to build or do this math and in math class we had to follow the math problem rule. They're way of expressing was different," "It required more thinking and creativity than during regular math class. We had to really put our brains to the test and create and calculate dimensions of various buildings and gardens" "The difference was that in WISEngineering, we had to communicate and understand each other's advantages and disadvantages.")

When students were asked if they enjoyed WISEngineering and why, the overwhelming majority reported that they enjoyed the project (87.8%). Students attributed their enjoyment of the project to a number of different factors. These included learning things in new ways (e.g., "I did enjoy WISEngineering because it showed me out of the box things," "I did enjoy doing WISEngineering because I could experiment with math and shapes"), the challenge of WISEngineering ("I did enjoy it because the projects were really fun and challenging," "because it involved thinking and smarts"), and the use of technology ("because it was fun working on new programs on the computer," "because I get to use new technology new software"). Students also noted that it helped them learn concepts better ("because it's creative and makes learning math easier," or "it was a great way to learn more in math"), and they liked the opportunity to build and create something ("I did enjoy doing Wisengineering because it was fun to build lots of things"). Moreover, one student noted, "At first I didn't [like WISEngineering], but then when the Community Garden came along I did because there was a challenge to it. I really enjoy challenges." Only five students said they did not enjoy their WISEngineering experience because they found it confusing, difficult, boring and a lot of work, and/or enjoyed other projects more.

5. Discussion

Results demonstrate that informed engineering projects in WISEngineering helped students develop understanding of Common Core mathematical concepts. Students in all three units significantly improved performance from pretest to posttest. Students also improved performance on state standardized tests surrounding the WISEngineering implementations. Comparisons to other students in the same district indicate that WISEngineering could have a significant impact on mathematics performance compared to typical instruction. These results align with other studies that find engineering design as an effective method to teach STEM concepts (Apedoe et al., 2008; Fortus et al., 2004; Kolodner et al., 2003; Penner et al., 1998; Roth, 1996) and extend technology-based approaches to scaffold general engineering design to learn middle school mathematics concepts.

Using an informed engineering design approach with specifications and constraints carefully targeted around Common Core concepts successfully helped students develop mathematical understanding. Students were able to use WISEngineering to learn and apply concepts such as ratio, proportion, volume and surface area to real-world challenges and develop their own solutions to design challenges. Similarly, using a knowledge integration framework supported students to elicit existing ideas, add normative mathematics ideas, develop criteria and reflect upon their understanding in the context of the design challenges.

Although students on average significantly improved performance on mathematics assessments, closer investigation of the individual units reveal that certain types of scaffolds may benefit different kinds of learners. For Community Center, less specific scaffolding and practice as well as the ability for students to dive into more complex topics like Euler's Theorem if motivated did not seem to benefit students classified as partially proficient. CC had a moderate effect on students categorized as proficient, and a large effect for advanced proficient students. For Community Garden, a unit with explicit instruction, guidance, and practice with feedback, the opposite trend occurred. CG had a medium effect on advanced proficient students, a large effect for proficient students and an even larger effect for partially proficient students. Balancing Act introduced difficult concepts with explicit scaffolding and visualization-based feedback. Balancing Act had a large effect on all groups, but a larger effect on proficient and advanced proficient students. These results resonate with an *expertise reversal effect* (Kalyuga, Ayres, Chandler, & Sweller, 2003), where more expert learners benefit from less explicit scaffolding. More research is needed to investigate the interplay between scaffolding engineering design and fundamental science or mathematics concepts with the learner's level of expertise. Research on appropriate levels of scaffolding and feedback is especially important in technology-enhanced environments capable of tailored instruction.

Although the pilot tests demonstrate that students can learn mathematics through WISEngineering, the pilot tests also point to further refinement of the technologies and curricular implementation. For instance, students were able to post their designs to the Design Wall and use the Design Wall to explore other students' designs, but few students carefully critiqued each others' designs according to specifications and constraints. Future revisions will investigate how to support design critiques. Similarly, students were able to use the Design Journal to check over their work, but did not use the Design Portfolio as part of their final presentation. Students presented their physical models to the class at the end or simply finished the project (in BA). Curricular revisions will focus on fostering reflection through more targeted use of the journal and portfolio.

Limitations to this pilot study involve transferability of these results to other populations. This study involved low-performing students in high-needs schools, thus results may apply to students in similar populations of economically disadvantaged and underrepresented groups in STEM. Additionally, comparison groups gave an indication of progress of WISEngineering to traditional curricula, but groups were not tightly randomized. These results indicate the potential of an informed engineering design approach to learning mathematics.

6. Conclusions

This paper presented results from pilot testing of the WISEngineering environment, an online engineering design system that scaffolds engineering projects for middle school students. Pilot tests resulted in significant student improvement on tests that measured understanding of Common Core mathematical concepts, as well as significant growth on state standardized tests. Results demonstrate that students using WISEngineering design challenges were able to use all units to learn Common Core mathematics concepts through scaffolded engineering design. In particular, WISEngineering units may hold particular benefit for social as well as conceptual learning for high-needs populations.

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