WISEngineering: Integrating Common Core Math Concepts in an Informal Setting

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Abstract

WISEngineering is a free, online learning environment that guides students through engineering design projects geared toward improving student learning in middle and high school science, technology, engineering, and mathematics (STEM) subject areas. WISEngineering combines an informed engineering design pedagogy\(^1\) with the Knowledge Integration learning framework\(^2\). WISEngineering is an extension of the Web-based Inquiry Science Environment (WISE) at the University of California-Berkeley\(^3\).

Instructional modules within WISEngineering scaffold engineering design while guiding students through hands-on design projects. These projects focus on an engineering design pedagogy that provides students an opportunity to engage with CAD and digital fabrication technologies in the classroom to create, build, and refine their designs. WISEngineering’s projects immerse students in engineering habits of mind such as systems thinking, creativity, optimism, and collaboration, in conjunction with standards-based mathematics and science concepts.

The Community Center Challenge (CC) project, formerly referred to as the Community Building Challenge (CBC), is a two-week long WISEngineering instructional module that asks students to design and construct a model for a new community center while facilitating instruction of Common Core Math Concepts (i.e. expressions and equations; ratios and proportions). The CC was piloted during the 2011-2012 school year in low-socioeconomic status, high-needs 7th grade classrooms in a school district in the midst of state takeover located on the east coast. The results from our pilot study revealed that students learned and applied their understanding of these Common Core Math Concepts to create and prototype solutions to address the design challenge\(^4\). Analysis of embedded assessments revealed that students used supports within WISEngineering to make connections between mathematical and engineering ideas.

As a follow up to the initial pilot study, an investigation was launched to determine whether a different population in a more informal educational setting would differ in the use of the supports provided within WISEngineering. This paper outlines the implementation of the CC in an informal summer educational seminar setting which involved 7th and 8th grade gifted participants (N=36) in June-July 2012. Statistical analysis of pretest and posttest measures along with embedded assessments, examined through the knowledge-integration framework are included.

Introduction

Changes in the modern world and the global economy indicate that the importance of science and mathematics is steadily increasing\(^5\). The number of science, technology, engineering, and mathematics (STEM) related careers, specifically in science and engineering, are increasing faster than other professions\(^6\). The recent report, *Engineering in K-12 Education*, by the National Academy of Engineering and the National Research Council suggests that individual STEM disciplines could be contextually integrated within engineering\(^7\). The past decade has
been witness to myriad efforts to incorporate engineering at the K-12 level; however, the report indicates that important aspects of engineering design are often neglected in existing curricula.

WISEngineering ([www.wisengineering.org](http://www.wisengineering.org)) was developed as a response to this report; to address some of the shortcomings observed in the review of K-12 engineering education programs. WISEngineering is a learning management system that guides students, step by step, through an informed engineering design process. WISEngineering incorporates teacher and researcher features that allow for the monitoring and assessment of student understanding. Embedded assessments allow teachers to examine student approaches to creating solutions for the design challenge presented at the beginning of a unit.

This system utilizes an informed engineering design pedagogy, which has been established and validated through several preceding projects. This approach to engineering design leads students through several curricular segments termed Knowledge and Skill Builders (KSBs). KSBs are targeted activities incorporating content knowledge necessary to develop design solutions. Students use the KSBs at various points in the web-based curriculum to ‘build’ on their existing understanding of the content. In the case of Community Center Challenge, students are working to understand mathematical features of a building, including three-dimensional shape properties along with volume and surface area components of a structure. The KSBs are designed to keep students away from the all too common trial-and-error approach to engineering design, which often fails to facilitate foundational conceptual understanding.

Previous work with WISEngineering suggests that such a technology-enhanced engineering design module was helpful in increasing student understanding of mathematics and engineering design processes in a formal educational setting. The purpose of this paper is to outline the implementation of the Community Center Challenge in an informal educational environment with gifted 7th and 8th grade students in the Mid-Atlantic region (N=36). Specifically, this study targets the following questions: 1) Can scaffolding engineering design and knowledge integration in WISEngineering result in increased understanding of Common Core mathematics concepts in an informal educational setting? 2) How can scaffolding knowledge integration help students make connections among STEM ideas in an informal educational setting?

**Background**

Formal education in the United States has been focused on preparing students for the workforce. Throughout the past decade, widespread attention has been devoted to increasing student involvement in STEM fields. All over the country, school districts have developed ways in which to integrate engineering education at the pre-college level.

In addition, several universities and science museums have programs that are making efforts to increase students’ engineering awareness, knowledge, and interest.

Many of these programs focus on combining one or several STEM disciplines through engineering, but the attention paid to aspects of the design process is inconsistent across programs. WISEngineering is unique in that it supports...
students through every step of an engineering design process. This support encourages students to develop engineering habits of mind as they progress through an authentic design challenge. Engineering habits of mind involve systems thinking, creativity, collaboration, optimism, communication, and taking into account ethical considerations\textsuperscript{9}. Informed engineering design assists in the facilitation of a design process that is more than building for the sake of construction\textsuperscript{1}; the engineering design process is intended to teach students how to organize their thinking and make informed decisions to come up with high quality solutions to problems\textsuperscript{10}. Many projects in WISEngineering leverage computer-aided design (CAD) and digital fabrication technologies (i.e. Silhouette Cameo die-cutting machine; See Figure 2) to provide students with a more authentic and contextualized experience.

**Curriculum Development and Knowledge Integration**

The foundation of all WISEngineering projects is the knowledge integration (KI) framework. KI is a research-based perspective that combines several prevailing approaches to learning within developmental, constructivist, sociocultural, and cognitive psychology. KI was founded upon the premise that students enter classrooms or engage in learning with intuitively formulated ideas about phenomena that are rooted in their experiential understandings of the world\textsuperscript{11}. The knowledge integration perspective suggests that learners create understandings through a process of adding, sorting, evaluating, distinguishing, and refining ideas from their wide-ranging participation in life (i.e. classroom, culture, and routine engagements). An instructional approach using knowledge integration pinpoints essential processes that assist students to connect related ideas to elaborate and develop their understandings. This perspective translates into an instructional approach that maps on very well to engineering design\textsuperscript{12}, and forms the basis for WISEngineering curriculum design, assessment, and subsequent revision.

The KI framework can be used to examine the connections students make among mathematical ideas and how students use those ideas to form a coherent mathematical understanding\textsuperscript{13}. This is useful because students often struggle in relating mathematics to their everyday experiences. In using knowledge integration to construct and evaluate these engineering design experiences, gaps in students’ understandings or a lack of connections between ideas can more easily be identified.

**Informed engineering design pedagogy**

Informed engineering design pedagogy is the foundation of the engineering design process utilized in WISEngineering curricula\textsuperscript{1}. This pedagogical approach encourages students to actually apply what they have learned to a given design challenge as opposed to solving the design challenge via trial-and-error methods. In this way, students devise solutions that are informed by content area knowledge provided in the Knowledge and Skill Builders within a project unit. The WISEngineering research and development team has found that this approach shows promise in using engineering design to improve mathematics learning.
The WISEngineering environment

WISEngineering is a free, online learning environment that is an extension of the open-source Web-Inquiry Science Environment (WISE). Whereas WISE provides online scaffolded inquiry projects, WISEngineering has fully online curriculum within each project that is guided by informed engineering design pedagogy using engineering design navigation that makes each step in the engineering design process explicit for students. Students unfamiliar with engineering design can benefit from the engineering design map that allows them to easily identify which segment of the engineering design process they are working within in the context of a project unit (See Figure 2).

WISEngineering contains several features, in addition to the engineering design navigation, that make it distinct from WISE. In terms of curriculum design, there are several steps for student activities that have roots in engineering design: the design journal, design portfolio, and the design wall. Each of these components is geared toward helping students ideate, craft, and share solutions. The design journal helps students get their ideas down by through an electronic sketchpad drawing tool. Students can manipulate and illustrate their own designs within the system. WISEngineering records all student data, so these initial ideas can be referenced at a later time. The design portfolio allows students to collect any of their work from the project unit and compile it into an electronic portfolio that can be shared with both peers and instructors. This feature is usually reserved for the end of project assessment or presentation. Finally, the design wall is used so that students may share sketches, ideas, and feedback with classmates, peers, and even other students participating in the same project in different settings or locations.

Community Center Challenge

This paper highlights an implementation of the WISEngineering project unit, the Community Center Challenge. The Community Center Challenge is a two-week design project originally designed for 7th grade mathematics students. This project gives students a scenario: A town named Willingdon has just decided to create a community center dedicated to helping people in the town. The mayor of the community is searching for young creative, and brilliant architects who can build a community center in Willingdon. The students are also given several specifications and constraints for this challenge; the community center needs to include 3 different three-dimensional shapes, stand up on its own, and serve the community in positive ways. As students are guided through the activities in the scenario (Table 1), explicitly entering different phases of the engineering design process followed in the unit, they ideate initial ideas, refine their designs using mathematical content knowledge, physically build and construct a cardstock prototype, and create a final design solution. The final design solutions must meet all specifications and constraints, meaning that the students engage with Common Core

**Methods**

*Design-based research methodology*

This research study uses design-based research methods common in educational research. The experiment is conducted in an informal education setting and has been designed to test theories of learning. Design-based research in this setting will facilitate design improvement and refinement of the curricular intervention for future use in informal educational settings. This study investigates how an informed engineering design pedagogy can facilitate student learning of standards-based mathematics using engineering design.

**Participants**

There were 36 total participants (n=36) in this study. These participants had enrolled in the Summer Enrichment Program (SEP) and had been identified as gifted based on criteria determined by the university that oversees the program. Based on a series of application essays and tests, these students were admitted to the program, which consists of three 2-week sessions. After admission to the program, students were given an opportunity to choose their academic coursework. These participants were rising 6th and 7th grade students, mostly from the mid-Atlantic region. *WISEngineering: Problem Solving Through Engineering Design* was offered as a seminar course for all three sessions during the 2012 SEP. This course’s main focus was the Community Center Challenge (CC) curricular unit so that students could gain exposure to engineering and develop their mathematical skills.

**Teacher and implementation**

One instructor was in charge of implementing the CC unit through three SEP sessions of *WISEngineering: Problem Solving Through Engineering Design*. This instructor was a former middle school instructor, familiar with pedagogical approaches relevant to teaching the population’s age group. Additionally, the instructor had been trained in Knowledge-Integration theory, had experience with Modelmaker CAD software and digital fabrication technologies, and was provided with a foundational understanding of informed engineering design. For each two-week session, the *WISEngineering* course was taught as an afternoon seminar that lasted 90 minutes for four days a week. Each session had less than twenty student participants. Content learning and enrichment was emphasized, and academic grades were not issued in this course.

**Table 1. Community Center Challenge Activities**

<table>
<thead>
<tr>
<th>Engineering Activity Steps</th>
<th>Community Center Challenge Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design Challenge</strong></td>
<td>Design challenge introduced, engineering design processes and map, design journal</td>
</tr>
<tr>
<td><strong>Specifications and</strong></td>
<td>Learners are given specifications and constraints for the</td>
</tr>
<tr>
<td>Constraints</td>
<td>project and confirm their understanding through embedded assessments</td>
</tr>
<tr>
<td>-------------</td>
<td>---------------------------------------------------------------</td>
</tr>
<tr>
<td>Develop Knowledge</td>
<td>Using online tutorials, students learn more about 3-D shapes and the calculations of surface area and volume. Pencil and paper calculation practice was provided to learners in these steps.</td>
</tr>
<tr>
<td>Ideate Solutions</td>
<td>Learners utilize Internet resources to find images of community buildings; they sketch designs in the design journal and share out with peers on the design wall</td>
</tr>
<tr>
<td>Build Prototype</td>
<td>Use ModelMaker (CAD) software and Silhouette digital fabrication machines to design, build, and construct models.</td>
</tr>
<tr>
<td>Evaluate Prototype</td>
<td>Post CAD designs to design wall to elicit feedback from peers. Hand calculations and CAD software calculations are used to check specifications and constraints and also to calculate cost.</td>
</tr>
<tr>
<td>Refine Design</td>
<td>Use evaluation and peer feedback to refine model designs</td>
</tr>
<tr>
<td>Finalize Solution</td>
<td>Decide on final design solution for the challenge presented; share work with peers and teacher(s).</td>
</tr>
</tbody>
</table>

Data Sources

The data collection consisted of paper pretest and posttest assessments (see Appendix A) and online embedded assessments (i.e. electronically stored answers to questions within the web-based unit). The pretest and posttest are identical; the pretest was administered prior to the beginning of the web-based unit, and the posttest was administered at the conclusion of the unit. The pretests and posttests were designed by teachers and university researchers to assess students’ engineering habits of mind, mathematical understandings, and interest in STEM subjects. Students’ embedded assessments will be evaluated using a KI rubric\textsuperscript{15} to discern the connections that students make between ideas. These assessments will show how the engineering design process featured in individual steps throughout the unit impacts students’ understanding of mathematics and engineering concepts.

Data Analysis

Each student’s pretest and posttest were scored. Out of the 15 items on the test, students received 1 point credit for a correct answer, 0 point credit for an incorrect answer. In this review of the data, no partial credit was awarded on the pre/post assessment. If a student omitted an answer to a question and completed the remainder of the test, the answer was counted as incorrect. Pre/posttest data was omitted for two students in the study due to lack of completion. Paired sample t-tests were used to examine the differences in students’ performance from pretest to posttest. Cohen’s \textsuperscript{16} d was used to calculate effect size.

The embedded assessment data for 3 distinct steps of the Community Center Challenge have been selected for analysis. These three steps are: 3.3 – What makes a 3-D shape a 3-D shape?, 5.3- Reflecting on your design, and 7.5 – Which 3-D figures roll the best?. Step 3.3 is designed to get students to articulate their understandings of 3-D objects in terms of geometric shape.
characteristics. Step 5.3 asks students to contemplate their proposed design for the community center by prompting a discussion of shape nets and reflection on students’ designs. Step 7.5 requires students to determine, from a list of 3-D shapes, which will roll best, and provide a justification. These steps have been evaluated using the Knowledge Integration Framework; as applied to this work, this framework is designed to measure the development of student coherent understandings and the integration of engineering, mathematics, and real-world ideas.

The Knowledge Integration framework informed curriculum design in this module. This framework will be used to evaluate the ideas that students express in open response embedded assessment items. Because students differ in the prior knowledge that they bring to a given academic task, the instruction in the CC unit follows the pattern of the framework which scaffolds student learning in ways that are designed to help students form a more coherent understanding of a topic. The scaffolding that is built into the unit is used elicit students’ existing ideas and add normative ideas to integrate into students’ existing knowledge. Following this sequence, students engage in design through the CC unit to distinguish among new ideas and prior knowledge through experience. Finally, students are given an opportunity to reflect on their understanding using system tools (i.e. design journal, design portfolio) and peer collaboration. This reflection provides students with an opportunity to sort out their ideas, identify deficiencies in their own understanding, and fill in any gaps as necessary. The KI rubric (Figure 2) here is based on a 6 point scale (0-5) that identifies normative student ideas and connections between them. The idea of this rubric is not to assess for write or wrong, but rather to evaluate student ideas, as they are elicited, for a coherent understanding of the content.

<table>
<thead>
<tr>
<th>Scoring Guide</th>
<th>Description</th>
<th>Student Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Complex link</td>
<td>More than two normative ideas are linked with a cohesive rationale that relates to and answers the question being asked.</td>
<td>Geometric solids you might use in this challenge is a cube, rectangular prism and a square pyramid (m5) because all of them have a base (m1) and can stand up on their own. (m3)</td>
</tr>
<tr>
<td>4 Simple link</td>
<td>Two normative ideas that are related to the question that have a normative link.</td>
<td>The three different geometric solids that we are using are a rectangular prism, sphere, and a cylinder. (m5) We would include these three geometric solids in this challenge because when we put all the shapes together as a building it looked like the ones we use in our community. (m7)</td>
</tr>
<tr>
<td>3 Partial link</td>
<td>Mentions one or more normative ideas related to the topic and question, but no cohesive normative links between the ideas exist.</td>
<td>I would possibly use a cube because it is the most interesting. I would like to also use a triangular prism because it is simple and easy. I would like to use a sphere because it would be cool to see a house in a ball form.</td>
</tr>
<tr>
<td>2 No link</td>
<td>At least one alternative idea is stated. An alternative idea is one that is related to the topic but is not answering the question and may or may not be correct. No normative link exists.</td>
<td>Three dimensional shapes have edges, faces, and vertices.</td>
</tr>
<tr>
<td>1 Irrelevant</td>
<td>Student answer includes irrelevant or incorrect information and there is no link between ideas. An irrelevant idea is one that is not even related to the topic.</td>
<td>A three-dimensional shape is interesting.</td>
</tr>
<tr>
<td>0 - No answer</td>
<td>Student answer provides no answer.</td>
<td>No answer provided</td>
</tr>
</tbody>
</table>

Figure 2. Sample KI Rubric for Embedded Assessments
The criteria for each rating is provided within Figure 2. Students' ideas are classified according to the ideas list generated for this unit (Figure 3).

![Figure 3. Coding for Students’ Ideas](image)

**Results**

Statistical analysis using paired samples t-tests show that there was a significant difference in the students’ performance from pretest ($M=11.74$, $SD=2.03$) to posttest ($M=12.54$, $SD=1.93$) assessments; $t(34)=-3.018$, $p=0.005$. The effect size for this analysis ($d=0.40$) was found to exceed Cohen’s $d=0.20$ convention for a small effect ($d=0.20$). These results suggest that gifted students in an informal setting participating in the WISEngineering Community Center Challenge had a small to medium effect on student outcomes from pretest to posttest.

The knowledge integration score of students’ embedded assessments for steps 3.3, 5.3, and 7.5, were calculated based on the ideas (Figure 3) identified in student responses. Interrater reliability for the individual idea coding was 89% calculated using Krippendorff’s alpha. The knowledge integration score (0-5) was derived based on the identified ideas.
A composite of the student responses in Steps 3.3, 5.3, and 7.5 (each bar represents a singular question), reveals that students participating in the Community Center Challenge were successful in linking mathematics, engineering, and real-world ideas to their prior knowledge. Students can successfully identify shapes and apply specifications and constraints in context. Approximately 87% of students’ responses across these three steps established a partial link or complete link between ideas. This analysis suggests that scaffolding within the CC unit has the potential to help students make connections among ideas in working toward a more cohesive understanding.

**Discussion**

Pilot testing done in the previous year with students in the classroom demonstrated that students made statistically significant gains from pretest to posttest. As with any learning intervention, a gain is to be expected; however, students in our initial pilot group also showed significant growth on state standardized tests. These results showed that students were able to learn Common Core math concepts through engineering design. The pilot testing also seemed to indicate that this was especially true for high-needs populations.

The students in this study are considered “gifted”, that is, more advanced in their understanding of certain subject matter. The growth demonstrated through the analysis is an improvement of roughly 1 point from pre/posttest scores. The outcomes of the pre/posttests in this study simply revealed that the unit did not appear to hinder student learning through the application of engineering to scaffold mathematics learning. What is not clear from the data provided is to what extent the WISEngineering unit can account for the Common Core mathematics concepts tested in this study.

The analysis of Knowledge-Integration composite across three steps indicates that students throughout the unit are making progress toward a more cohesive understanding of their material. Students are making connections among ideas, though they are not always normative, as is indicated in the criteria for KI-3. Additionally, the KI codes reveal that students often focus on
one idea; if they are discussing one to two ideas, they don’t seem to make as many of the desired connections. More elaborate scaffolding within the unit, along with supplemental instruction, may help further to encourage student thinking. After analyzing the responses to the selected steps, it is possible that the KI-4 may be inflated due to the nature of the question being asked or to in-class instruction that was not directly observed.

The implementation of the Community Center Challenge in an informal setting did not come without challenges. On a couple of occasions, there were technical difficulties that complicated the fabrication process. However, on those occasions when the 2-D die cutting machines would not cooperate, students were given the alternative of scissors, glue, and tape, to physically construct the models they designed in the CAD software. All students involved in this project were able to use the CAD software for the design of their building. These students worked in teacher-selected groups of 2-3 for the duration of the project.

Limitations

This particular study is limited in that any findings can only be generalized to the sampled population. The pre/post assessment items and unit scaffolding may need to be modified for gifted populations, like the one in this study. While there was no ceiling effect, it seems plausible that students rushed through the pre/post assessment items because they either thought they were too simple or because they lacked motivation that they would have in a traditional classroom environment. A comparison group, one that is exposed to more traditional methods of instruction for this topic, would have been useful.

Conclusion

This paper presented results from the application of WISEngineering in an informal environment involving gifted students. The results revealed a statistically significant improvement from pretest to posttest for students involved in this study. Students improve in their understanding of Common Core mathematics concepts through a scaffolded engineering design project. Discovering the degree of meaningfulness provided by this statistic requires further investigation considering other variables such as student affect and time on task, as well as through the modification of tests based on the selected population. Results of knowledge integration analysis of three selected steps reveal that students are successful in connecting mathematical, engineering, and real-world ideas, in the context of a scaffolded engineering design project. WISEngineering units may be beneficial to gifted students in informal settings, but further research endeavors are warranted to understand all of the benefits and drawbacks involved in scaffolding engineering design for mathematics learning.

Bibliography


