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Investigating Secondary Students' Engagement with Web-based Engineering Design Processes

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Abstract

The National Academy of Engineering suggests that K-12 engineering education should focus on the process of engineering design[1]. Similarly, the Next Generation Science Standards incorporate engineering design processes alongside scientific inquiry in K-12 settings[2]. Using engineering design as a medium through which to learn related STEM content has shown promise[3] yet it may be difficult for precollege instructors to incorporate into their practice because many K-12 teachers and students lack explicit exposure to engineering design. Students who do engage in engineering projects often rely on trial-and-error approaches that may or may not connect to deeper conceptual understanding, or focus heavily on building structures without engaging in other design processes[4].

Modeling engineering design explicitly can help students develop design fundamentals, much like the principles of cognitive apprenticeship or explicit models of inquiry [5,6]. WISEngineering is an online learning environment that scaffolds engineering design for precollege students with demonstrated learning outcomes[7]. Instructional modules within WISEngineering guide students through hands-on design projects. In addition to providing students with opportunities to engage with CAD and digital fabrication technologies, projects within WISEngineering are structured to correspond with authentic engineering design processes (i.e. iteration, generating multiple solutions, prototyping, etc.) using an informed engineering design pedagogy[8].

This study investigates what kinds of engineering design processes middle school students engage in with WISEngineering. Although projects in WISEngineering suggest a sequence of steps to complete design projects, students can navigate freely within the environment. Using log data from students engaged in a Community Garden design project, we will investigate how scaffolding informed engineering design can help students become involved in engineering design processes. Classroom observations combined with the analysis of system log file data to explore the time devoted to various engineering design processes will help us answer the following research questions:

1. How can scaffolding engineering design processes through WISEngineering help middle school students engage in authentic engineering practices?
2. What types of patterns in design processes do students exhibit?

Results from this study will inform other precollege engineering educators about how to support design projects in authentic classrooms as well as illustrate common design patterns for middle school students.

Introduction

The process of engineering design is critical to engineering education[1]. The National Academy of Engineering outlines four aspects of engineering design, namely that it is "(1) highly iterative; (2) open to the idea that a problem may have many possible solutions; (3) a meaningful context for learning scientific, mathematical, and technological concepts; and (4) a stimulus to systems thinking, modeling, and analysis" (p. 4). Engineering design has also been defined "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".[9] With the incorporation of engineering into the Next Generation Science Standards, engineering design becomes increasingly important in K-12 settings. Precollege students and teachers are now charged with understanding engineering concepts and processes, such as defining problems, developing models, planning investigations, analyzing data, using mathematics, information technology, or computational thinking, designing solutions, and engaging in argument from practice[1]. In these settings it is also important to understand how engineering design can serve as a context for learning science and mathematics concepts, similar to Dym et al.[10]

Although engineers use a variety of design processes in practice, many K-12 students have little to no explicit exposure to engineering design processes. In schools without dedicated engineering classes, engineering projects are infused into science and mathematics courses. Yet precollege science and math teachers often have little experience with engineering. Thus, many students that engage in engineering projects use trial-and-error approaches that often do not connect to deeper conceptual understanding[11] or focus heavily on building structures without engaging in other processes of design.[4]

Drawing from principles of cognitive apprenticeship[5] and success of explicit models of scientific inquiry[6], guiding students through explicit models of engineering design processes can help students and teachers understand design processes. Although there is no "one" engineering design method, providing some kind of explicit support for students can help provide insight into understanding and undertaking engineering design, particularly for precollege settings[12]. Text-based methods to model and support engineering design have been successful in such programs as Project Lead the Way[13] and Engineering is Elementary[14]. However, technology-enhanced environments have specific affordances to help support learning and model authentic practices[15, 16, 17, 18, 19]. Technology-enhanced environments can provide similar benefit to engineering education[20]. For example, students working on a CAD program can share and critique other students' designs within an environment that prompts them to reflect upon and refine their designs based on evaluations. Online environments also have unique opportunities for research, such as logging and tracking student progress that can give insight into processes that may contribute to learning outcomes[21].

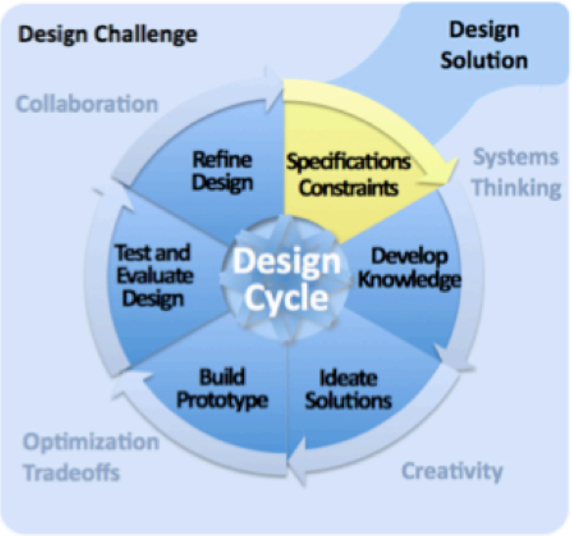
This work-in-progress paper aims to understand how explicitly supporting engineering design in an online environment can help precollege students engage in design processes through novel use of log data.

WISEngineering: Using Informed Engineering Design Pedagogy

The WISEngineering learning environment helps precollege students engage in engineering design projects by providing an explicit model and steps that reflect design processes[7]. Based upon Web-based Inquiry Science Environment (WISE) technologies, WISEngineering is a free, online learning environment where students proceed through design projects at their own pace[22]. WISEngineering has a number of features such as an online design journal, design portfolio, and design wall where students can post their ideas and designs and get feedback from other students in their class[23]. Pilot tests with students using WISEngineering projects demonstrate that students made significant gains from pretest to posttest on measures of Common Core-based mathematical understanding for all three units as well as gains on standardized state mathematical tests compared to students in comparison classes[7].

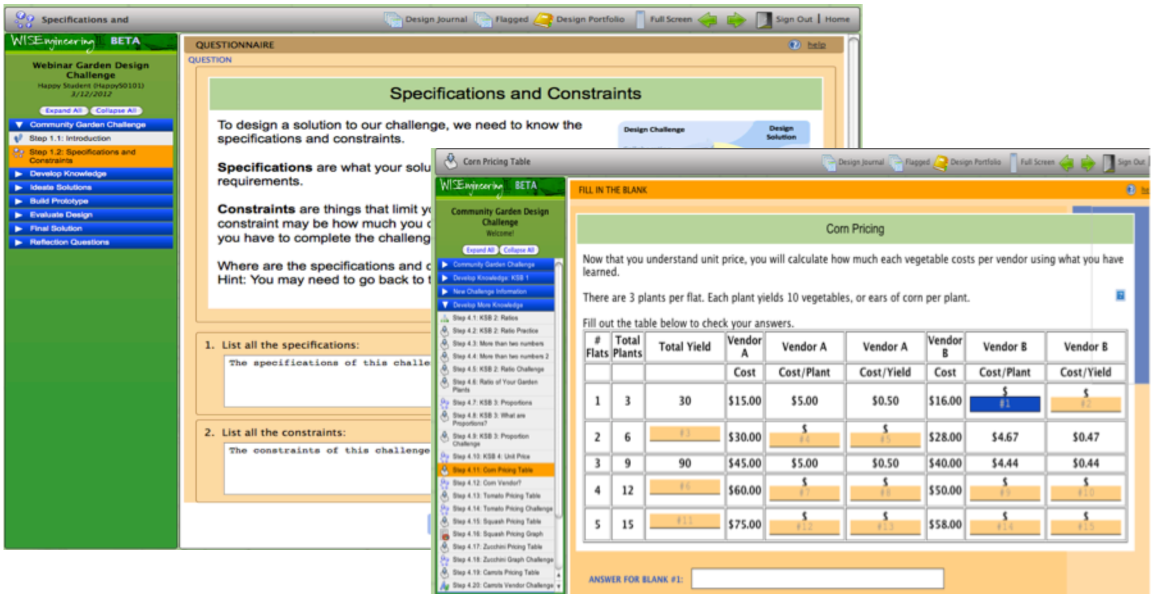
Projects within WISEngineering use an *informed engineering design pedagogy* to help make engineering design processes explicit for middle and high school students[8]. In this approach, students engage in specific activities that align with design processes, namely: Specifications and Constraints; Developing Knowledge; Ideate Solutions; Build Prototype; Test and Evaluate Design; and Refine Design (Figure 1). Each project in WISEngineering is broken down into steps that contain activities that align to each of the specified design processes. Students engage with the steps using the navigation screen (Figure 2).

The informed engineering design pedagogy focuses on learning science and mathematics concepts through carefully designed specifications and constraints followed by learning activities for the targeted content (Developing Knowledge; KSBs). This targeted approach embedded in an engineering design cycle helps students focus and learn



- ***Specifications and constraints*** – design challenges have particular specifications and constraints to emphasize particular concepts to be learned.
- ***Develop Knowledge (KSB)*** – A consideration of the specifications and constraints lead to investigation or inquiry into related concepts needed to solve the problem.
- ***Ideate Solutions*** – Ideating encourages students to develop multiple, *appropriate* solutions to the task at hand.
- ***Build Prototype*** – Selecting from their potential solutions, students construct virtual models or real-life prototypes.
- ***Test and Evaluate Design*** – Students test designs and evaluate whether they satisfy the project criteria.
- ***Refine Design*** – Based on tests, students revise designs to optimize their solutions.

Figure 1. An informed engineering design model. 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.



Specifications and Constraints

To design a solution to our challenge, we need to know the specifications and constraints.

Specifications are what your solu
requirements.

Constraints are things that limit y
constraint may be how much you c
you have to complete the challeng

Where are the specifications and c
Hint: You may need to go back to t

1. List all the specifications:

The specifications of this challe

2. List all the constraints:

The constraints of this challenge

Corn Pricing

Now that you understand unit price, you will calculate how much each vegetable costs per vendor using what you have learned.

There are 3 plants per flat. Each plant yields 10 vegetables, or ears of corn per plant.

Fill out the table below to check your answers.

# Flats	Total Plants	Total Yield	Vendor A	Vendor A	Vendor A	Vendor B	Vendor B	Vendor B
			Cost	Cost/Plant	Cost/Yield	Cost	Cost/Plant	Cost/Yield
1	3	30	$15.00	$5.00	$0.50	$16.00	$ #1	$ #2
2	6	#3	$30.00	$ #4	$ #5	$28.00	$4.67	$0.47
3	9	90	$45.00	$5.00	$0.50	$40.00	$4.44	$0.44
4	12	#6	$60.00	$ #7	$ #8	$50.00	$ #9	$ #10
5	15	#11	$75.00	$ #12	$ #13	$58.00	$ #14	$ #15

ANSWER FOR BLANK #1:

Figure 2. Activities in WISEngineering correspond to the informed engineering design cycle. Each step within a design phase consists of a variety of types, for example, a table where students calculate and get feedback on ratios of corn prices for different vendors.

relevant content knowledge that is motivated by the project goals. For example, in the Community Garden project, students are charged with designing a community garden within certain size and budget constraints that force them to use ratios and proportions in their solution. The WISEngineering environment guides students through an informed design process through specific activities and steps that correspond to each design phase (Figure 2). For instance, students first focus on specifications and constraints, then a developing knowledge phase. Each step within design phases consists of a variety of types, ranging from questions for students to answer in multiple-choice or free-response short-answers to creating drawings, or sharing designs with other classmates through the design wall. For example, the fourth activity in the Community Garden project guides students through a series of steps that help students understand ratios through practice and feedback on calculating prices of vegetables from various vendors (Figure 2).

This paper presents first steps to understand how log data from the WISEngineering system can provide insight into what kinds of design processes students engage in with specific scaffolding. Capturing how students engage in design processes typically requires researchers to observe or videotape design teams and/or conduct interviews with project teams. WISEngineering steps specifically correspond to certain design phases, such as developing knowledge, prototyping, or evaluating their designs. Although these steps are provided, students are free to navigate wherever they would like within the WISEngineering system. The log data can potentially serve as another form of evidence of design processes that students may engage in during the projects; the log data may have importance in understanding how students are involved in engineering design during WISEngineering projects. For example, students may quickly skip through specifications and constraints until they design their own first solution, then go back and check the parameters of the project. Certain students may spend a lot of time drawing and designing an initial solution, whereas others may spend more time iterating and testing their designs. Log data enables quantitative investigation of patterns on a larger scale, which can ultimately complement qualitative observations and interviews of students. Thus, this paper presents a work-in-progress aiming to answer the following questions: How can scaffolding engineering design processes through WISEngineering help middle school students engage in authentic engineering practices? What kinds of patterns of design processes do students exhibit?

Methods

Curriculum. This paper focuses on students engaged in the Community Garden Challenge (CG), which charges students with designing a garden to maximize vegetable output with heights of plants and cost as specifications and constraints. CG focuses on Common Core mathematics concepts of unit price, unit rate of change, and proportions. Within the project, students plan, design, and create a physical model of their garden. CG was designed to last for two weeks.

Participants. Seventh graders in two general mathematics classes from one school participated in this study. Students attended one of the lowest performing schools in a district currently under state takeover. In this school, a small proportion of students were classified as advanced proficient in math (10.6%), and language arts/literacy (2.2), compared to the state (Math: 24.4%, LAL: 12.4%). Many students were eligible for individualized education plans (12.6%), and/or classified as having Limited English Proficiency (28.6%). Students worked in groups of 2-4, consistent with other WISE and engineering projects. The teacher involved with the project chose the mathematics classes to use the WISEngineering unit to replace her existing curriculum on ratios and proportions. The teacher attended two days of professional development.

*Data Sources and Analysis***.** The data used in this work-in-progress paper were log data from students' interactions with the WISEngineering environment. WISEngineering captures when students click on what step, how long they stay on each step, and what they do within steps (for steps that involve students generating an answer to a question or drawing, etc.). Steps within WISEngineering can be configured to lock, requiring a student response to proceed. This implementation of the project allowed students to navigate freely between steps; time spent, in conjunction with project products, can be used to indicate if students were engaged in mindless clicking or were spending substantial time in each step of the process. Log data were collected from the 20 participating student groups (n=42 individual students). Two students who were absent for the first week were removed from analysis.

Averages and totals for steps visited and time per activity (corresponding to design phases) were calculated from log data across student groups. Since different activities have different number of steps (for example, Develop Knowledge (4) has 20 steps whereas Build Prototype (6) only has 2 steps), average time per step was calculated for each design phase.

Results

On average, students spent a little more than 257 minutes in the WISEngineering system over the course of three weeks. The students constructed models of their community garden designs offline, and also received explicit instruction from the teacher on days they were not in the computer lab with WISEngineering.

The Community Garden project in WISEngineering has 44 explicit steps for students, but the average number of steps visited by the student groups averaged 138.8, with large variation across groups (SD=60.71). Most students roughly followed the order of steps provided by WISEngineering, but jumped from step to step within design processes (e.g. within Develop Knowledge) as well as across design processes (e.g. from Develop Knowledge to Specifications and Constraints) accounting for the larger number of steps visited than contained in the project.

Looking across the design phases, students on average spent the most time per step in the building prototype and developing knowledge design phases. Students spent the most average time per step in the Build Prototype Phase. The build prototype phase consisted of two steps. In the first step, students used the WISE drawing tool to sketch out a plan for their garden. The second step had instructions for students to build the prototype using a silhouette printer. The second and third design phases that students spent the most time in on average were the developing knowledge phases. The first developing knowledge phase guided students to develop spatial knowledge to make 3D shapes from 2D paper to make a physical model of a garden (Activity 2). The second developing knowledge phase (Activity 4) consists of many practice steps of students learning about ratios and then applying their knowledge to calculate ratios of their chosen garden plants and associated costs. The teacher had a large impact on the time students spent in these phases. She made sure students completed through activity 4 to get the practice with ratios and proportion.

On average, students spent very little time in the phases of testing, evaluating and refining their design. These phases occurred at the end of the project (Activities 7-9). Students also spent less time per step with specifications and constraints (Activities 1 and 3) and Ideation (Activity 5).

Table 1. Means and standard deviations for time in each design phase, average time per step, and total time and steps for WISEngineering student groups.

	Time (in minutes)		**Range**		**Steps per design phase**	**Average time/step**
	M	**SD**	**Min**	**Max**		
1. Specifications and Constraints	**11.7**	**12.2**	**0.5**	**41.2**	**4.0**	**2.9**
2. Develop Knowledge	**74.6**	**55.5**	**24.0**	**224.9**	**5.0**	**14.9**
3. Specifications and Constraints	**4.9**	**7.3**	**0.0**	**22.6**	**2.0**	**2.5**
4. Develop Knowledge	**96.2**	**50.7**	**30.9**	**208.0**	**20.0**	**4.8**
5. Ideate Solutions	**10.7**	**14.4**	**0.0**	**60.4**	**4.0**	**2.7**
6. Build Prototype	**58.2**	**38.2**	**0.8**	**135.0**	**2.0**	**29.1**
7. Evaluate Design	**0.6**	**0.8**	**0.0**	**2.5**	**2.0**	**0.3**
8. Refine Design	**0.2**	**0.4**	**0.0**	**1.7**	**2.0**	**0.1**
9. Reflection	**0.1**	**0.2**	**0.0**	**0.5**	**2.0**	**0.0**
Average total time	**257.1**	**106.5**	**103.2**	**483.7**		
Average total steps	**138.8**	**60.7**	**68.0**	**330.0**		

Discussion

This paper presents a first look at log data from middle school students engaged in the Community Garden design project in the WISEngineering design environment. WISEngineering guided students through activities that corresponded to explicit design phases from an informed engineering design model. Students tended to spend most their time building prototypes, similar to results from studies of undergraduate students[4]. However, students also spent a large portion of their time in phases focused on learning and practicing the targeted Common Core-based mathematics content of ratio and proportion.

The number of steps student groups visited within WISEngineering indicated that students were going back and forth between steps. According to the data reviewed to date, most students followed the steps in an ordinal sequence. Typically, students jumped from step to step within a single design process (e.g. sub-steps within Develop Knowledge) as well as across design processes (e.g. from Develop Knowledge to Specifications and Constraints) which led to the higher average of steps visited. Overall, results suggest that using scaffolded engineering design approaches in WISEngineering can help students focus on important conceptual understanding, which is extremely important if engineering is to be well integrated into in precollege settings. Further analysis of log data is necessary to determine if there are any definitive patterns that indicate which steps were frequently visited and what other steps were prompting students to go back for more information. The navigational patterns can be used to understand students' use of an engineering design process as well as to investigate and refine instructional design aspects of the project.

Results also point to the utility of log data to help researchers gain insight into the kinds of design processes that students may engage in during design projects. While log data should not serve as a stand-alone assessment for how students were involved in these scaffolded engineering design activities, it is a critical piece of evidence to show what steps are most utilized by students. The results form this work-in-progess study suggest that students spend a majority of their time on designing and building prototypes to meet the goal of the design challenge. They spend less time, on average, testing, evaluating, and refining their designs. This is most likely due to classroom time constraints and the pressure for teachers to move on to the next curricular unit. While students are able to create a product, it is important that future implementations give further consideration to the testing, evaluation, and refinement processes, as they are essential to the iterative nature of engineering design.

Next steps for this work-in-progress include looking for emerging patterns in the log data that may correspond to documented student learning gains (pre-/posttest). We also look to corroborate log data with qualitative classroom observations and video data to ensure the reliability of these findings. We look to extract information about the design steps in which students are engaged and to determine how to best scaffold certain activities within WISEngineering projects in the context of an authentic precollege classroom environment. These next steps will inform future work, in terms of potentially connecting students' experiences (i.e. using pre/post survey data to gauge their understanding of engineering design) with engineering design and learning outcomes, testing student understanding of an engineering design process, and the creation for professional development materials for teachers prior to the implementation of WISEngineering projects, as the results also point to the importance of the classroom teacher's role in facilitation.

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