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Promoting Productive Disciplinary Engagement in Engineering Design Using a CAD tool

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Abstract: Engaging young students with the engineering design process and scaffolding the learning of effective design thinking skills is an ongoing endeavor for engineering education researchers. In this design and deployment paper, we describe the design of an innovative curricular material using a computer aided design (CAD) tool for promoting productive engagement with disciplinary practices of tradeoffs and design optimization. We present preliminary qualitative findings from our design based research study that indicate the effectiveness of our intervention and highlight ongoing as well as future work by our team to advance the community's understanding of how to effectively scaffold the learning of effective design thinking skills via technology as well as curricular materials.

Keywords: Engineering design, design thinking, tradeoffs, computer aided design, design journal

1. Introduction

Over the last decade, there has been a growing attention towards engineering design education amongst K-12 as well as undergraduate education researchers. An improved understanding of the engineering design practices has been identified as being critical for preparing a highly-skilled workforce that is ready to tackle the 21st century challenges. At the heart of the engineering design process is the practice of making tradeoffs (Dym, Agogino, Eris, Frey, & Leifer, 2005). Students have to make connections between multiple design variables, evaluate multiple and often competing solutions based on the design goal, and take design decisions that lead to an optimal design (Dym et al., 2005; Silk & Schunn, 2008). However, students find it challenging to engage with this process and connect multiple parameters to make effective tradeoffs (Zohar, 1995).

In this paper, we suggest a way of tackling this challenge and supporting middle school students' productive engagement with the engineering design process using a computer aided simulation (CAD) tool called Energy3D (available at http://energy.concord.org/energy3d). CAD tools have been found to scaffold students' design thinking process and promote productive work (Kern & Crippen, 2013). These tools afford quick simulation and testing of design ideas. While the use of CAD tools to support the engineering design process is not new, we have designed companion scaffolds to support the integration of Energy3D within the middle school curriculum by providing immediate feedback to the students and helping them connect multiple variables and make effective tradeoffs. Specifically, in this paper, we ask – how can we help students make effective tradeoff decisions and promote design thinking.

2. Framework

2.1 Design thinking

Design thinking involves the systematic process of generating, evaluating, and specifying solutions that satisfy a given set of constraints and meet users' needs (Dym et al., 2005). This characterization emphasizes a process where engineers investigate the solution space using a combination of convergent and divergent thinking to determine the extent of the goal (scope), develop ideas for possible solutions (generate), assess the ideas and check their fit in the solution space (evaluate), and implement their ideas to achieve the intended goal (realize) (Dym et al., 2005; Sheppard, 2003). This is done iteratively to optimize the solution, a process that involves maximizing the "functionality of a design with respect to the design requirements and the resources available" (Silk & Schunn, 2008, p. 5). Design optimization is a continuous process that requires engineers to use design thinking in order to deal with uncertainty due to multiple solution paths or "design trajectory" (Vattam, Helms, & Goel, 2008) that are resolved by making tradeoffs (Dym et al., 2005; Kroll, Condoor, & Jansson, 2001).

Silk and Schunn suggest that "tradeoffs occur both when considering the input variables of a system, those that can be manipulated in the system design, and the outcome variables, those that are used to judge the quality of the design… when a choice to modify the level of one variable impacts the effect of another variable on the outcome… also occur when weighing the different outcomes of a design, such as when considering the cost of a design compared to its effectiveness" (Silk & Schunn, 2008, p. 20). Thus, being able to reason with multiple interacting variables in an engineering system and understand their effect on the design goal is essential for making tradeoff decisions.

This paper investigates how to support this process of making effective tradeoff decisions by using a CAD tool. The next section explains the research setting and the instructional unit designed to be used along with this CAD tool.

3. Method

3.1 Research setting

This study was part of a larger design based research study that was conducted in a middle school in the Midwest US. A total of 421 students participated in this larger study across three grades – sixth (143 students), seventh (152 students), and eighth grade (126 students). The larger study spanned two weeks with 45 minute lessons every day. Every student was given one laptop running the Energy3D software and worked individually on three design tasks. However, individual work was interspersed with whole class discussions led by the teacher. Researchers were present in the class everyday to facilitate and assist the teacher in resolving technical questions about the software. Classes were taught by the respective teachers at every grade level by following a detailed lesson plan provided by the researchers.

3.2 Instructional design

We followed the Learning by Design framework (Kolodner et al., 2003) to guide the instructional activities. This framework couples the engineering design cycle along with the science inquiry cycle. Table 1 below gives an overview of the sequence of activities in the instructional unit.

Table 1: Sequence of activities in the instructional unit.

1. Introduce energy efficient buildings and Energy3D software.
2. Critique a suboptimal model representing poor design choices.
3. Introduce the big design challenge – 'Design a low-cost energy-efficient home in Indianapolis for your principal.'
4. Sub-challenge 1: Learn about solar radiation
    a. Students work on the first sub-challenge – 'Design a one-story house in Indianapolis that captures the maximum light from the sun in the winter.'
5. Sub-challenge 2: Learn about heat transfer
    a. Students work on the second sub-challenge – 'Design a one-story house in Indianapolis that maintains a temperature of 20 degrees Celsius (or 68 degree Fahrenheit) inside the house throughout the year and consumes the least energy.'
6. Solve the big design challenge introduced in step 3 using concepts learned from sub-challenges 1 and 2.
7. Share final designs with the class and facilitate peer-review.

On the first day of using Energy3D, the teachers introduced students to the software and gave a demo of the different functionalities. This was followed by students doing individual work; critiquing a house representing poor design choices. Students had to write their critiques in the design journal given to them. Teachers then introduced the students to the big design challenge but students had to first work on the two sub-challenges as preparatory activities for solving the big design challenge. Students also received a handout with summary of science-concepts related to energy efficiency. Students were prompted to refer to these science concepts while working on their design solution and complete the relevant section of the design journal while working on the design tasks. Figure 1 shows the Energy3D interface that students used to construct their energy efficient designs.

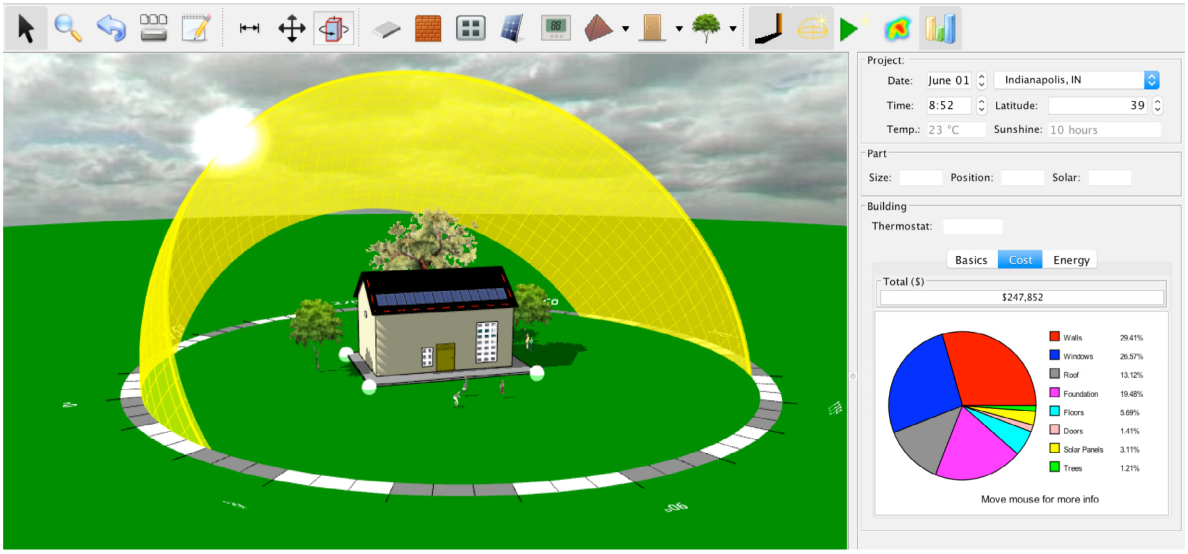

Figure 1. Screenshot of the Energy3D software

In preparation for the big challenge, students had to complete two smaller sub-challenges focused on the concepts of solar radiation and heat transfer. While working on these sub-challenges, they had to complete the design journal and record 'what they know', 'what they needed to know' and 'what did they learn' along with evidence and explanation for each observation. Students worked individually on these sub-challenges but switched to whole class discussion led by the teachers during software feature demonstrations. Once students had completed these sub-challenges, they started working on the big design challenge on their individual laptops. They had to write their design decisions and tradeoffs by hand in their paper-based design journal. Appropriate prompts were provided by the teachers and the journal to scaffold this process. After completing their big design challenge, students presented their final designs along with their design rationale and were evaluated by their teacher.

3.3 Data collection and analysis

The dataset for this paper comprises of the design journals, student-generated designs and student responses to a design scenario that was presented after students worked through the unit. The design scenario asked students to select the best design out of two building designs. It presented total cost and energy consumed by the two building designs- Building 1 with no solar panels (cost: $140,439; net energy consumed: 10074 kWh) and Building 2 with solar panels (cost: $142,939; net energy consumed: 7486 kWh). We analyzed the data qualitatively, doing content analysis, to identify patterns in the student responses. The next section presents preliminary findings from this analysis.

4. Findings and Discussion

Preliminary findings suggest that majority of the students were able to make effective tradeoff decisions in the design scenario after working on this unit. Across all the three grades, 74% students selected Building 2's design as the optimal design. Within the different grade levels, 78% students (grade 6), 74% students (grade 7), and 70% students (grade 8) selected Building 2's design as the optimal design. Students potentially learned about the long term benefits of the solar panels and that it helped offset the high installation cost by iteratively modifying their solutions to the design challenges in the instructional unit. They selected design #2 (or building 2) as the better option out of the two and reasoned that although this design was more expensive out of the two choices, the energy savings afforded by the solar panels would eventually compensate for the cost of the design. For instance, student S259 (grade 7) reasoned that – *"[Building 2 is better] because building 2 [is] only a little bit more expensive but it uses a lot less energy."*

Our initial analysis indicates that during the unit, students optimized their design iteratively, making tradeoffs and modifying different input parameters and seeing the effect on the outcome parameters as well as weighing the outcome parameters. This potentially informed their design choice as they were responding to the design scenario question above. For instance, while working on the final design challenge (step 6 in the instructional sequence – big design challenge) student S259 iteratively improved the design of the house by modifying the input design parameters and observing the effect on the outcome parameter.

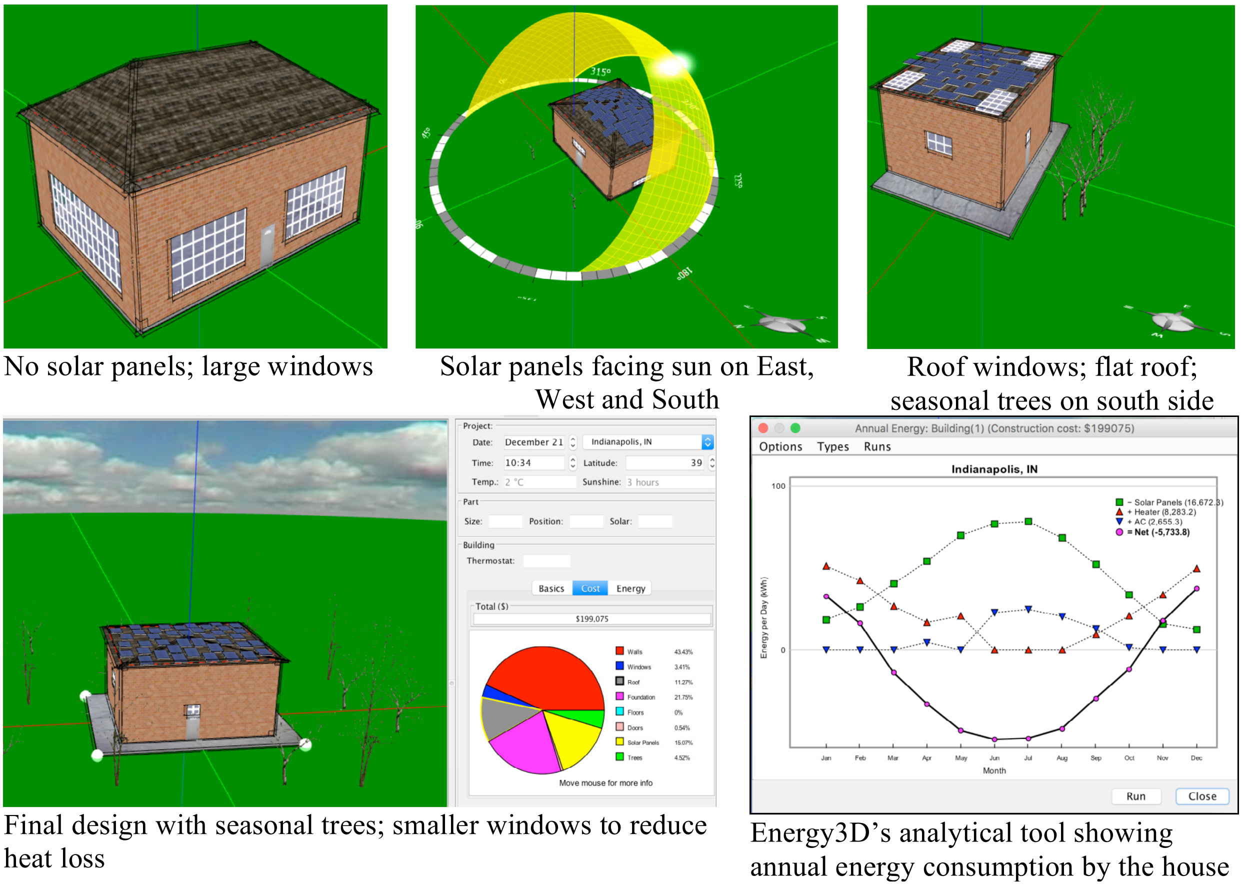

Figure 2. Some stages and sequence of design decisions by student S259 (grade 7)

Figure 2 shows some of the stages from student S259's design process. S259 first started by constructing a house without any solar panels and having large windows to capture more sunlight. The student made a note of the relationship between heat loss and insulation in the journal- *"Heat loss can be reduced by adding insulation because heat can't escape through the insulation."* The student then determined that it was beneficial to use the solar panels and used the position of the sun to determine where to place those panels. The student placed solar panels on the east, west and south directions facing the sun in order to capture direct sunlight (the sun is predominantly on the southern side of the house in Indianapolis as shown by the yellow arc in the second figure). S259 referred to the cost of the design and the energy consumed to determine the effect of placing solar panels at specific locations. Next, the student modified the roof to include windows that allowed more solar energy to enter the house and thus reduce the heating bill in the winter. S259 also tested a flatter roof design arguing that this may allow more solar panels to face the sun directly. After each modification, the student ran the energy analysis and reviewed the cost of the design. The student also added trees on the south side facing the sun. These types of trees shed their leaves in the winter and thus allowed sunlight to fall on the house in the winter thus reducing the heating bill but provided shade in the summer to keep the air-conditioning bill low. However, with the same insulation and window thickness, larger and more windows meant greater heat loss from inside the house. S259 eventually removed these windows from the roof after understanding that these were causing too much heat loss. The student recorded in the journal— *"I have 4 windows because if you have more windows your energy cost will go up."* Simultaneously, S259 reduced the size of other windows in the house as well to further reduce heat loss. So finally, the student settled for the design which had more seasonal trees surrounding the house, had smaller and fewer windows and had solar panels directly facing the sun.

Thus, the design journal offered opportunities for the students to reflect on their design decisions and document their observations and explanations for easy reference both during and after the design process. It provided opportunities for students to connect what they already knew about the design problem with new knowledge gained from working on the multiple design challenges. Students conducted systematic investigation and tested different variables (e.g., size and number of windows, insulation, direction of solar panels, trees, etc.) The feedback offered by Energy3D's analytical tools potentially helped the students make connections between multiple variables by showing how the design modifications affected the cost and energy consumption of the house.

These preliminary qualitative findings indicate that this curricular unit using the design journal along with the CAD software potentially helped the students make connections between multiple variables and take effective tradeoff decisions. We are in the process of doing a rigorous analysis of the entire dataset to confirm these preliminary findings. It will also be important to understand differences between the three grade levels and how we can scaffold grade specific requirements based on the specific needs of the students. Another important part of ongoing as well as future work is the integration of the design journal with the Energy3D software. We are working on digitizing the journal and making it easily available in the same workspace as the CAD tool instead of a separate paper handout. In future, we also intend to provide automatic and personalized feedback to the students based on their observations and explanations noted in the design journal.

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