Exploring Students' Experimentation Strategies in Engineering Design using an Educational CAD Tool

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Abstract - Engineering design is an iterative process that supports the solution of problems by applying scientific knowledge to make informed decisions. Assessing different levels of expertise in experimentation is a difficult task since these are not usually visible as part of a student's final design solution. The purpose of this research is to investigate and characterize students' experimentation strategies while working on a design challenge. We conducted a concurrent think-aloud to capture students' thinking while they were working on a design challenge using an educational computer-aided design (CAD) software. We showed how the design replays generated from the log files collected from the CAD software can be used to represent students' experimentation strategies and how these representations can be validated by the data collected from the think-aloud. Our preliminary results show that technology-based assessment by the educational CAD tool allows us to identify the differences between different experimentation strategies and that the result of this assessment is supported by the result obtained from the concurrent think-aloud. Implications of this work would be relevant to engineering educators and researchers who are interested in understanding and assessing students' experimentation strategies in engineering design.

Keywords – engineering design; experimentation; think-aloud; assessment

I. INTRODUCTION

A. Assessing Student Proficiency in Engineering Design

Engineering design is a key skill for everyone facing ill-structured problems that do not have a single solution or path to solve it. This process identifies a problem by considering its context, propose alternative solutions, build prototypes, evaluate them, and refine them iteratively [1-2]. The solutions then are context dependent, and there is not a single appropriate design for a problem.

The open-ended nature of engineering design makes it difficult to assess. Student proficiency in engineering design is challenging to assess effectively from a final design product, or by using traditional assessment instruments. Assessing student proficiency in design involves understanding the steps they follow to find a solution for a problem. As a consequence, some qualitative approaches have been evaluated to assess the design process (e.g., [3-7]). Nevertheless, there is not yet a reliable approach to assess these types of open-ended tasks, and the qualitative techniques are not scalable [8]. Technology-based assessments comprise a promising set of approaches to overcome these limitations [9]. By capturing students' interaction with computational tools such as computer-aided design (CAD) tools, we may be able to study and understand students' design process in a non-intrusive manner. Some of the technology-based approaches that have been explored are described by [8,10-13]. For example, [8] describes a computational approach based on time series analysis to assess engineering design processes whereas [11] describes the use of machine learning on hand-coded video data in identifying general engineering design patterns.

B. Beginning Designers vs. Informed Designers

The Informed Design Teaching and Learning Matrix [14] describes nine key design strategies employed by informed designers as compared to beginning student designers. In this matrix, the design process is deconstructed in order to better connect novice learning to expert literature and support informed teaching with engineering design activities [14].

One design strategy discussed in the Matrix, *conducting tests and experiments*, is an important strategy as students design to come up with the best solution possible. While experimenting, beginning designers run few or no tests on their design prototypes. When they perform tests, they conduct confounded experiments by changing multiple variables in a single experiment, which yield little understanding about potential solutions. Informed designers, however, run valid tests as part of technological investigations that help them to learn quickly about design variables, understand how things work, how the variables might be interconnected and optimize the performance of the prototypes they decide to develop.

Although experimentation is an important component of informed design behavior, it is hard to assess the different levels of students' expertise in experimentation as they are not usually visible as part of a student's final design solution. What makes this assessment harder is the open-ended and iterative nature of the experimentation process. Various teaching strategies have been recommended to encourage effective experimentations. One example strategy designed by [15-16] involves asking students to plan and conduct controlled scientific experimentations where they identify a single product feature to vary, control all other variables, and then measure product performance outcomes. However, this task can be challenging for educators without knowing the exact level of students' expertise in the experimentation process. Being able to identify and classify students' experimentation strategies would allow educators to better understand students' performance in conducting effective experiments as well as to offer interventions that could help students to conduct experiments that are more effective. The research question for this research is: *How do logged data generated by the educational CAD tool represent different experimentation strategies described by students?*

II. BACKGROUND

A free, open- source computer-aided design (CAD) software, Energy3D (www://energy.concord.org/energy3d/) was used in this research. This is a user-friendly software designed for educational research purposes that allows users to design and build energy efficient buildings. Energy3D collects data such as process data and a logger of student actions in the background as student design. An example of student design in Energy3D is shown in figure 1.

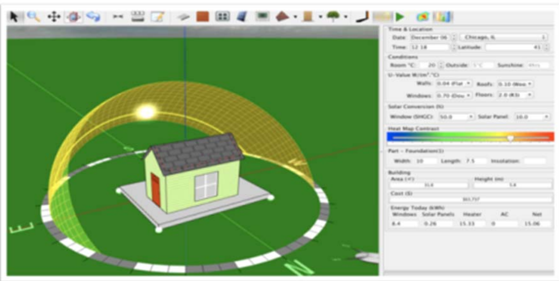

Figure 1. Example student design in Energy3D

III. METHODS

The purpose of this research is to (1) investigate and characterize students' experimentation strategies by conducting a think-aloud protocol to capture students' thinking while working on a design challenge using an educational CAD tool and (2) validate if the technology-based assessment by the educational CAD tool is a good representation of students' actual experimentation strategies.

A. *Participants*

Participants of this study consisted of two students (freshman) majoring in Computer Information Technology at a Midwestern University during the 2016 spring semester. Students were invited to participate voluntarily in two sessions comprising the research protocol.

B. *Procedures*

The research process was broken down into two sessions - Session 1: Students were introduced to Energy3D and were given a chance to explore and use it while working on an assignment; Session 2: Students worked on a design challenge to design an energy efficient building. A think–aloud protocol was carried out to capture students' reasoning while working on the design challenge. There was a one or a few days gap between session 1 and session 2, depending on students' availability.

During the first session, students were introduced to the study and signed a consent form. Then, students were told to watch two videos (each 4 mins long) on demonstrating how to use Energy3D. After that, students were given 35 mins to work on an assignment which aims at giving them a chance to use and get familiar with Energy3D. Students were then given a usability survey as soon as they were done with the assignment. Lastly, the first session was closed with semi-structured interview from the researcher. All instruments used during the first session are out of the scope of this paper. During the second session, students were introduced to the design challenge with design criteria explained to them. Then, they were given 30 mins to work on the design challenge. After that, they were given an intervention which aimed at asking students to reflect on a case study related to confounding experiments. This case study involves a scenario where a student was trying to figure out what factor (sunlight, water, or fertilizer) helps a plant to grow better while varying two variables (sunlight and water or sunlight and fertilizer) at the same time. The purpose of this case was to indirectly guiding them to realize the need of varying only one variable at a time while experimenting. They then were given another 30 mins to complete the design challenge. Lastly, the second session ended with an exit interview that collected students' perceptions and comments about Energy3D and the study in general. Figure 2 below summarizes the steps conducted during Session one and two.

The scope of this paper focuses on student experimentation strategies for the second session of the protocol. Hence, we will explore how different experimentation strategies described by the students are represented in the logged data.

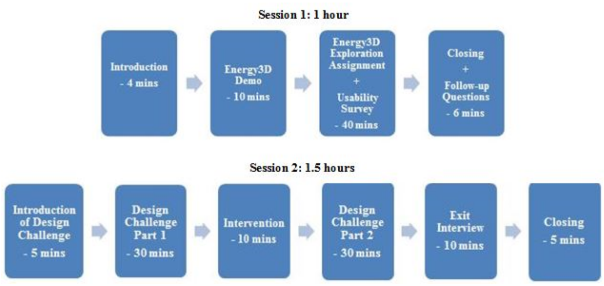

Figure 2. Procedures

C. *Design Challenge*

The design problem presented to the students required them to design an energy efficient building that maintains a comfortable interior temperature throughout the year by considering the use of solar energy. Design criteria are presented in Table 1.

TABLE I. DESIGN CRITERIA

Criteria	**Description**
Energy	Minimize energy needed to keep the building comfortable throughout the year. Preferably zero net energy consumption if possible.
Cost	Minimize total cost of the building. Cost cannot exceed $250,000 in building materials.
Size	Comfortably fit 4 adults (approximately $200m^2$). The house's platform must not exceed the 28 x 36 m platform provided in the software.
Location	The building should be located in Indianapolis, Indiana.
Components	Each side of the house must have at least one window. Do not add more than 40 solar panels. Tree trunks must be outside the house. Only one structure on the platform. Do not make any walkway or ramp around the house. There is no need to design interior structure such as rooms. Do not place humans inside the hose and do not use more than two humans.

D. *Data Collection*

The Energy3D software records every action performed by the students in the form of log files. These include actions such as sketching buildings, adding and removing components, running energy analysis, etc. These log files can then be used to reconstruct the entire student design process, called a design replay, to present a compressed view of the process in a shortened amount of time. Graphs will be generated from the design replay. In addition, students' responses recorded from the think-aloud were transcribed and used to validate the inferences made from the design replays.

E. *Data Analysis*

The graphs generated from the design replays and the think-aloud transcriptions were reviewed by researcher characterizing students' experimentation behaviors/patterns as well as validating the inferences made from the design replays using students' reasoning from the think-aloud transcriptions.

The researcher classified students' experimentation strategies as either systematic or unfocused by looking at the number of iterations of systematic experiments that students performed. In this study, an experiment is considered as systematic if it follows an iterative sequence of steps which include (1) Build or modify a prototype, (2) Collect and analyze data on specific variables, (3) Modify these variables in the prototype.

IV. RESULTS

The result from this study shows two different types of experimentation patterns observed from students, which are systematic and unfocused.

A. *Systematic Experimentation*

Student 1 (S1) spent most of the time in the first session constructing the house with reasoning for why certain components were build. Energy analysis was run towards the end of the first session to get a sense of the energy efficiency of the initial design. During the intervention, S1 was able to point out that varying one variable at a time during an experiment is essential to ensure the success of the experiment. During the second session, S1 was going back and forth between collecting and analyzing data on specific variables and modifying these variables to optimize the energy efficiency of the house. We consider this pattern as systematic experimentation. In addition, S1's actions were supported by the responses recorded during the think-aloud, which can be seen on Table 2.

TABLE II. S1 RESPONSES DURING SESSION 2

"After I added more windows, everything (energy consumption) went up. I am going to remove some." *" Now I want to change the position of solar panels and test it again."* *" I will add more trees, may be just to prevent heat from getting inside the house, and I will test it again."*

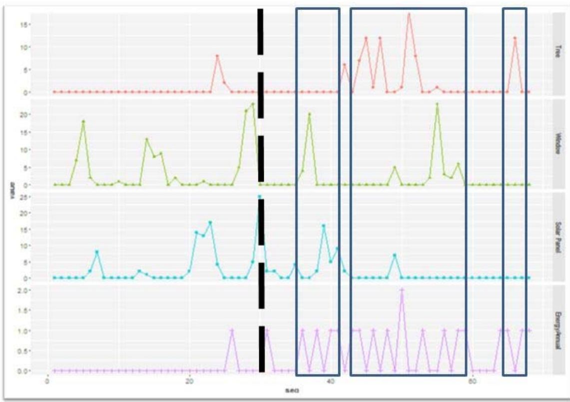

Figure 3. S1 actions with Energy3D (dotted black line: intervention; orange line: modify/add trees; green line: modify/add window; blue line: modify/add solar panel; purple line: energy analysis)

From figure 3, the red, green and blue lines before the solid blue bar represent S1's actions on constructing the house with different components whereas the purple line represents the energy analysis done by the student. On the other hand, the blue boxes in the figure show the relationship between S1's actions in altering the different components of the house and the energy analysis ran by the student during the second session of the design challenge. It can be seen that S1 was going back and forth between collecting and analyzing data from specific variables (e.g., trees, windows, solar panels) and using the analysis to then inform modification of these variables as part of iterative experimentation process.

B. *Unfocused Experimentation*

S2 spent most of the time in the first session constructing the house without clear reasoning for why certain components were built. A few rounds of energy analysis were run towards the end of the first session to get a sense of the energy efficiency of the initial design. During the intervention, S2 was not able to point out that varying one variable at a time in an experiment is essential to ensure the success of the experiment. Instead, S2's response was off topic and unrelated to the intervention. During the second session, S2 ran fewer rounds of energy analysis. In addition, S2 did not follow the process of collecting and analyzing data on specific variables and modifying these variables. Instead, S2 either ran energy analysis without modifying any variables or modified variables without running energy analysis within a specific window of time. We consider this pattern as unfocused experimentation. In addition, S2's actions were supported by the responses recorded during the think-aloud, which can be seen on Table 3.

TABLE III. STUDENT 2 RESPONSES

" For windows, I just have no idea. I made one for every wall just because I had to." *" Trees help in the summer, but during winter, it makes it colder., and I don't know how to prevent that."*

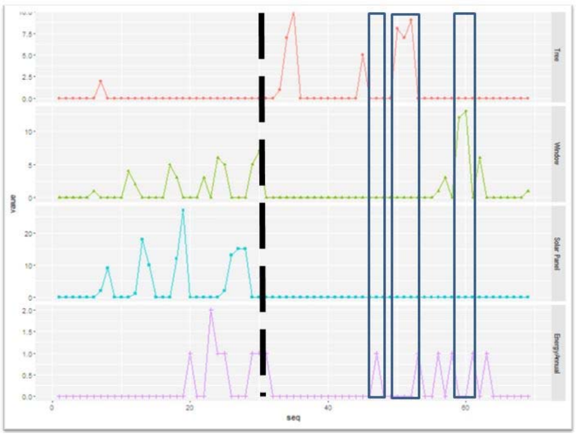

Figure 4. S2 actions with Energy3D (dotted black line: intervention; orange line: modify/add trees; green line: modify/add window; blue line: modify/add solar panel; purple line: energy analysis)

From figure 4, the red, green and blue lines before the solid blue bar represent S2's actions on constructing the house with different components whereas the purple line represents the energy analysis done by the student. On the other hand, the blue boxes in the figure show the relationship between S2's actions in altering the different components of the house and the energy analysis ran by the student. It can be seen that S2 was running fewer rounds of energy analysis and most of the analysis were not a result of any modification of variables.

V. CONCLUSIONS AND FUTURE WORK

Based on the result obtained from this exploratory study, we conclude that the technology-based assessment by the educational CAD tool allowed us to identify the differences between different experimentation strategies. Also, it does represent students' actual experimentation strategies. Future work will involve collecting more data from more students as well as developing a code scheme to code the transcriptions obtained from the recorded think-aloud.

VI. LIMITATIONS

This research investigated two students (freshman) majoring in Computer Information Technology from a Midwestern University during the 2016 spring semester. Even though this sample size is small, it does represent a differentiated group of students with basic knowledge about heat transfer and solar energy and the interest of exploring design behaviors. This preliminary research aims at sampling few students from a very homologous group. Although the data set is small for now, the results encourage us to continue this research path.

VII. ACKNOWLEDGMENT

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