Characterizing students' design strategies during simulation-based engineering of sustainable buildings

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Abstract

This is a research paper. Investigating the use of design strategies is one of the most important approaches in understanding the design thinking processes of students in engineering design. Understanding students’ use of design strategies—specifically, generating ideas, conducting experiments, revising and iterating, and troubleshooting—allows educators to better help students improve in their design thinking processes. In this study, we aimed to investigate and characterize students’ use of four design strategies while they were designing with an educational CAD tool. Using students’ captured videos and think-aloud transcripts, we have identified and characterized patterns of students’ four design strategies. In this study, we have classified students into five categories based on their design patterns and descriptively identified the least and most prominent patterns students implemented.

Keywords: design strategies, design thinking, generating ideas, conducting experiment, revising and iterating, troubleshooting.

Introduction

Engineering design is an iterative decision-making process of generating, evaluating, and specifying concepts for systems or components to meet desired requirements [1]. Design thinking, which includes cognitive, strategic, and practical aspects of a design processes, is a crucial part of engineering design. Due to their strategic nature, design thinking processes should be taught and learned through design strategies such as those described in the Informed Design Teaching and Learning Matrix [2]. In this study, we investigated students’ use of four design strategies—namely, 1) generating ideas, 2) conducting experiments, 3) revising and iterating, and 4) troubleshooting. Generating ideas is one of the most important design strategies, as it promotes idea fluency by brainstorming to avoid fixation, and encourages more divergent thinking to be a better future problem solver. Conducting experiments is another key design strategy, as it promotes conducting valid experiments and testing to learn more about the materials, design variables, and how systems work. Our goal is to guide students towards conducting multiple and valid experiments by changing one variable at a time. Revising and iterating strategies promote continuous and iterative improvement by changing variables in systems and components multiple times. Troubleshooting promotes concentration on problematic areas, and finding ways to determine and fix problems that might be encountered during the design process.

Assessing students’ proficiency in engineering design is a challenging process due to its’ open-ended nature. It is often not enough to assess students’ proficiency in design thinking only from the final product, as one needs to interpret all the steps taken to make the final product to solve a problem. There have been some studies that characterized students’ experimentation and generating ideas strategies in engineering design [3, 4, 5]. However, students' use of four design thinking strategies at the same time has not been assessed and categorized based on their strategic performance.

Therefore, the purpose of this research is to investigate and characterize students' generating ideas, conducting experiments, revising and iterating, and troubleshooting strategies while working on a design challenge with the help of an educational CAD tool. The research question investigated was: What are students' patterns of design thinking strategies while solving a design challenge using an educational CAD tool?

Methods

A. Participants

Participants of this study included 12 first-year undergraduate students, four from First Year Engineering, seven from Engineering Technology, and one from Mathematics. These students were invited to participate in a one and half hour-long study voluntarily. A series of screening questions were asked to make sure that we selected students with similar levels of prior design experience. Students were challenged to build an energy-efficient and aesthetically pleasing house using Energy3D, a simulation-based CAD tool for designing 3D buildings and power stations [6]. These students had no prior experience with the Energy3D software. These students were given certain constraints and requirements as part of the challenge, such as the area of the house should be approximately 200 m^2 and the budget of the house should not be more than $200,000. The data source we used for the analysis consisted of the actions and design behaviors students performed as they interacted with the Energy3D software for the first 40 minutes of the study.

B. Procedures

The research protocol of this study was carried out with one student at a time. Observing one student at a time allowed the researcher to better facilitate the process of think-aloud as well as screen recording. Students worked individually and each student came up with their own design. The entire protocol took only one session that lasted one and a half hours. A day before coming into the session, students were informed by email to watch a five-minute-long video about how to operate the Energy3D software [7]. Students were also provided with a one-page-long handout of scientific concepts relevant in designing an energy efficient home. The next day when students came into the session, they were first given time to read and sign the consent form, then an entrance survey was conducted. Subsequently, students were introduced to a design challenge that they needed to work on, which consisted of building an energy efficient house using Energy3D software under certain requirements and constraints. Right after the introduction, students were given 20 minutes of pre-training time where they became familiar with Energy3D by constructing a house using the software.

Once the pre-training was completed, students were introduced to an intervention where they were informed about four design thinking strategies, which were generating ideas, conducting experiments, revising and iterating, and troubleshooting. Students were then asked to incorporate these design thinking strategies into their design and make their house energy efficient for another 20 minutes. As students worked on solving the design challenge, a concurrent think-aloud protocol [8] was performed to capture students' verbalized design strategies. In addition, their screens were also captured using a screen capture tool OBS Studio (Open Broadcaster Software) [9].

C. Design Challenge

In this study, students were tasked with completing a design challenge where they had to design an energy efficient house using Energy3D software, while fulfilling some design requirements and constraints. The requirements and constraints of this design challenge were as follows:

- Cost of the house cannot exceed $200,000
- House should comfortably fit 4 adults (Area of the house should be around 200 square meters).
- Each side of the house must have at least one window.
- Number of solar panels should not exceed 40 (regardless of their conversion efficiency).
- The house's platform must not exceed the default platform provided in the software.
- Tree trunks must be outside the house.
- Only 1 structure on the platform should be made (no doghouses, detached garages, etc.).
- Walkway or ramp around the house should not be made
- Interior structures such as rooms, floors, or stairs should not be designed.
- Humans should not be placed inside the house and no more than 2 humans should be used.

D. Data Analysis Method

Data analysis process of this study was broken into eight steps. First, all of the videos were transcribed and checked manually twice by watching the videos and listening the audio recordings at the same time to understand the depth of the data. Then, a coding scheme was developed to interpret students' generating ideas, conducting experiments, revising and iterating, and troubleshooting activities. Table 1 shows the coding scheme developed along with the descriptions and examples.

After the development of a coding scheme, the first round of data analysis was conducted. During this round, we made sure to exclude the initial construction activities such as students putting the four walls together, adding the roof for the first time, and other actions performed to build the house during the first 20 minutes.

Table 1: Codes used to analyze student design thinking strategies

Category	Code	Description	Sample examples
Generating Ideas	GI	Episodes in which the students generate new ideas by divergent thinking, brainstorming	"I completely forgot about the trees! I am gonna try placing some trees now."
Conducting Experiment	CE	Episodes in which the students change one variable at a time to learn about the materials, key design variables and the system work	"Okay. And now, let me try the roof thing, changing the color of the roof. I'm gonna try black roof but then white walls. Okay. Let's see how that works out. "
Revising and Iterating	RI	Episodes in which the students use iteration to improve ideas based on the feedback	"I'm gonna reduce the size of my windows because I feel like it go way too low to the ground and like even without energy efficiency, that's just the risks for them to be broken."
Troubleshooting	TS	Episodes in which the students focus on problematic areas and propose ways to fix them by diagnosing and troubleshooting ideas based on simulations and tests	"So one of the main things, well two things I want to prioritize are um, the size of the house because I'm very near the maximum size of 200 square meters. So that's going to take a lot more energy to just heat and cool that. So if I minimize that to closer to about 150, that should reduce that energy. And then also I was considering putting trees around to add some shade and that will reduce the AC energy. especially around the trees here around the windows."

After construction activities, all of the generating ideas, conducting experiment, revising and iterating, and troubleshooting activities were color-coded based on the codes described on Table 1. The unit of analysis was the actions performed within a minute. When an activity was taking less than a minute, rounding was used for simplification. After all the color coding was done for all of the participants, we normalized the timing of all color-coded activities to fit the 20-minute time interval. Figure 1 depicts a sample of the color coding of the action for a particular student.

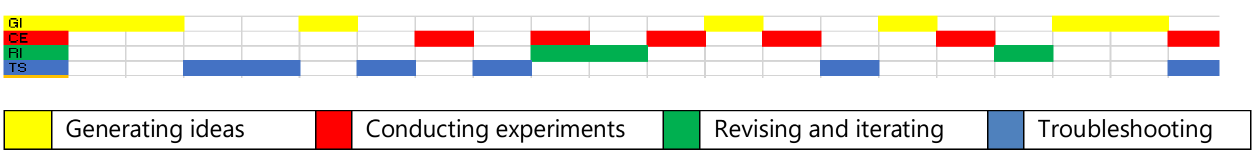

Figure 1: Sample visual color-coded representation for Student 5

After coding each student's activity for each minute, we calculated the percentage of time spent on each strategy. Based on these calculations, we grouped students with similar patterns and gave them labels. Once we determined students' pattern of four design strategy use individually, we then categorized them based on their most prominent patterns using the categorizations described on Table 2. We assumed low level as anything less than 25% and high level anything more than 45% and mid-level anything in between. We created five categorizations with the description of each of the primary pattern identified.

Table 2: Categorization of students based on the most prominent design patterns

	Fixated and unfocused	Fixated but focused	Fixated but balanced	Diverse and balanced	Diverse but focused
Four Design strategies Performance	Low generating ideas performance but high troubleshooting performance.	Low generating ideas performance but high revising and iterating performance.	Low generating ideas but mid-level of conducting experiments, revising and iterating and troubleshooting.	Mid-level of generating ideas, conducting experiments, revising and iterating and troubleshooting.	High level of generating ideas and conducting experiments.

Results and Discussion

Results of this study show all the design patterns students used including: generating of ideas, conducting experiments, revising and iterating, and troubleshooting within the 40-minute timeline. Based on that, students' percentages for each design strategy were calculated as presented on Table 3. Relevant observations include: S8 had the greatest percentage of idea generation during the challenge (i.e., 45%) whereas S12 never generated a new idea during the intervention (i.e., 0%) and instead spent more time on revising and iterating the house (i.e., 47.50%). On the other hand, S7 spent most of their time by conducting experiments on the ideas they were generating (i.e., 40%), however S1 never conducted experiments (i.e., 0%) but instead concentrated on finding ways to fix the problems they were facing—namely, using the troubleshooting strategy (i.e., 50%). Moreover, S5, S6, S7 and S11 were more diverse and balanced in their strategy use. In addition, all of the students met with design constraints except S6 was over the budget and S4 did not have an energy efficient house.

Table 3: Students' generating ideas, conducting experiment, revising and iterating and troubleshooting activities percentage.

Student #	Generating Ideas	Conducting Experiments	Revising and Iterating	Troubleshooting
S1	20.00%	0.00%	30.00%	50.00%
S2	10.00%	25.00%	55.00%	10.00%
S3	15.00%	35.00%	20.00%	30.00%
S4	10.00%	15.00%	30.00%	45.00%
S5	35.00%	25.00%	12.50%	27.50%
S6	35.00%	20.00%	27.50%	17.50%
S7	35.00%	40.00%	12.50%	12.50%
S8	45.00%	35.00%	15.00%	5.00%
S9	15.00%	25.00%	37.50%	22.50%
S10	22.50%	20.00%	50.00%	7.50%
S11	22.50%	25.00%	35.00%	17.50%
S12	0.00%	32.50%	47.50%	20.00%

To identify patterns of similarities and differences among the twelve students, we used a stacked bar graph to visualize the percentages of strategies used (see Figure 4). The x-axis represents each student in this study and y-axis represents the four design strategies performance by each student.

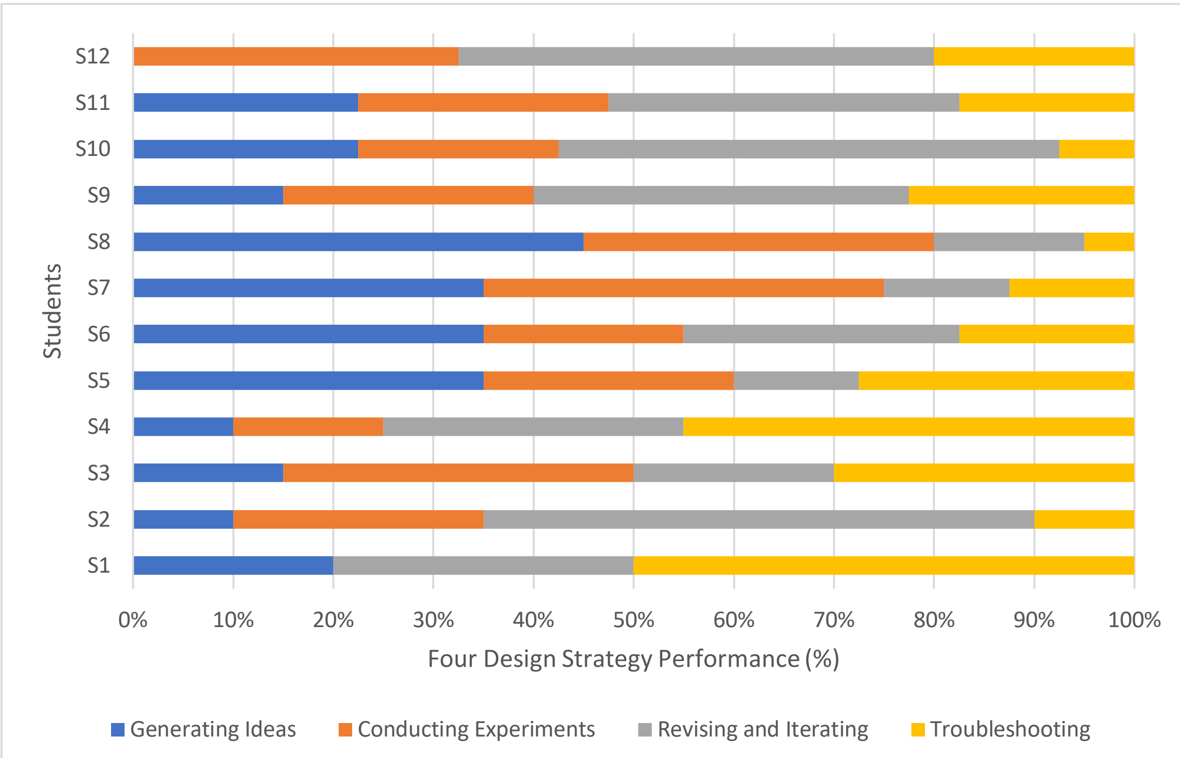

Figure 4: Students' distribution of the four design strategies.

Based on the patterns visualized in Figure 4, five basic groups were identified as follows:

1. Fixated and unfocused group: This group of students fixates on some initial ideas and finds ways to solve the problems.
2. Fixated but focused group: This group of students fixates on fewer ideas or does not generate any new ideas but revises them systematically.
3. Fixated but balanced group: This group of students fixates on some initial ideas but refines them systematically.
4. Diverse and balanced group: This group of students generates multiple ideas and implements multiple systematic and effective strategies.
5. Diverse but focused group: This group of students generates a lot of ideas and tests them in regular basis to see how the system works.

Figure 5 presents the distribution of students into the five groups or categories identified.

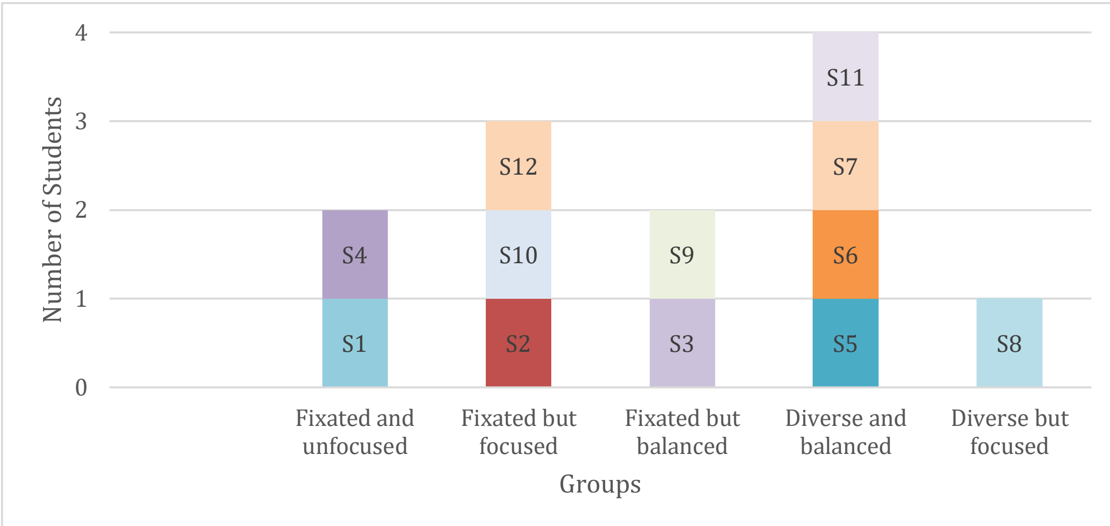

Figure 5: Distribution of students among the five categories describing their patterns in their strategy used.

As shown in Figure 5, several students fell into the diverse and balanced group, with 4 students on this group. On the other hand, only one student fell into the diverse but focused group which was S8.

Conclusion, implications and limitations

In conclusion, this study described the ways in which students used four design strategies during an engineering design challenge: generating ideas, conducting experiments, revising and iterating, and troubleshooting. This study also identified five different patterns of design strategy use. Finally, this study classified students into the five categories based on their design patterns and descriptively identified the least and most prominent patterns students implemented. As shown on Table 3, S1 and S12 had 0% of conducting experiments and generating ideas performances respectively, which was surprising. This pattern suggests that students may not use design strategies naturally and that learning experiences should identify ways to elicit or remind students to use multiple strategies. One limitation of this study was that we used one-minute chunks in the data analysis, which did not give high granularity, but was necessary to simplify the analysis. For future work, we plan to explore students' four design strategies usage with a bigger sample size and for a longer time. We might also include a second intervention to encourage students' optimum design strategy usage that might result in better design performances.

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