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Managing Uncertainty in CAD-enabled Engineering Design Tasks

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Managing uncertainty in CAD-enabled engineering design tasks

Purdue University

Abstract: Having to deal with uncertainty is a central feature of engineering design due to its open-ended, ill-structured, and underdetermined nature. While engaging in engineering design tasks, student designers might encounter uncertainty related to unfamiliar math and science concepts, as well as the uncertainty associated with using novel technological tools. It is important for students to learn how to deal with uncertainty as it is a crucial element of engaging in engineering and science practices. In addition, it is also important for educators to know how to engage and help students with the uncertainty faced. In the past, studies have been done in the science domain, focusing on studying how students deal with uncertainty through argumentation. However, studies of similar nature still lack in the domain of engineering design. In addition, studies that focus on CAD-enabled engineering design tasks are also missing. Therefore, this study examined the ways first-year undergraduate students managed uncertainty while engaging in CAD-enabled engineering design tasks. Data were gathered through the think-aloud protocol (i.e., students' verbalized thoughts while working on the engineering design tasks), as well as the recordings of students' computer screens as they worked on the engineering design tasks. Data analysis entailed the use of verbal protocol analysis/video analysis. Findings from this study presented the different types of uncertainty faced by students, how they managed them, as well as how that impacted their design performance. Implications of this study include a better understanding of the various ways students dealt with uncertainty, suggestions for how educators can help students manage uncertainty more effectively, as well as increased knowledge of ways that CAD can be used to help students manage uncertainty in engineering design tasks.

Keywords: uncertainty, engineering design, CAD, design thinking.

Introduction

Engineering design is a complex process that typically involves open-ended and ill-structured problems that often come with uncertainty, such as insufficient information or unclear requirements [1], [4]. In engineering education, students might face uncertainty when they design due to lack of relevant scientific and mathematical knowledge, or unfamiliarity with technological tools such as CAD [8]. Due to the degree of uncertainty associated with engineering design, the ability to handle uncertainty is one of the main characteristics of engineering design thinking [4]. Therefore, it is important for students to learn how to manage uncertainty as part of engineering and scientific practices. In fact, scholars in the field have urged for uncertainty to be included as a central part of engineering education [11].

"Managing uncertainty refers to behaviors an individual engages in to enable action in the face of uncertainty" [8, pp. 494]. Typically, students are expected or motivated to reduce uncertainty by trying to gather as much information as possible to either accept or reject a claim about something they are working on [5], [8]. However, that doesn't mean reducing uncertainty is the only way to deal with uncertainty. In fact, it might not always be the desirable way to deal with uncertainty. Students can also deal with uncertainty in other ways, such as raising more uncertainty, maintaining, or ignoring it, depending on the different situations that they are in [5], [8]. Some scholars actually argued that uncertainty is an important element in the process of

learning [7] because it creates disequilibrium that allows students to realize and work with the inconsistencies between their own understanding and new knowledge so that they can eventually come to new understandings [2], [6].

In order to better incorporate uncertainty into engineering education, it is first important to understand how students manage uncertainty in the context of engineering design. Understanding how students deal with uncertainty can inform educators of ways to address and teach uncertainty in the classrooms. Past studies have shown that in the science domain, work has been done on investigating how students manage uncertainty through argumentation (e.g., raise, maintain, reduce) [2], [5]. However, studies of similar nature still lack in the engineering design domain. Even though there was a study that investigated how students manage uncertainty during collaborative engineering problem solving [8], studies that focus on CAD-enabled engineering design tasks are still lacking.

Therefore, the purpose of this study is to investigate the ways first-year undergraduate students managed uncertainty while engaging in CAD-enabled engineering design tasks. The research questions are (a) what types of uncertainty did students face while working on a CAD-enabled engineering design task? (b) how did students manage uncertainty while working on CAD-enabled engineering design tasks? And (c) how did the ways students manage uncertainty impact their design performances?

Methods

Setting and Participants

The participants in this study included six first-year undergraduate students from a Midwestern University, who had some background in design thinking, either through their engineering majors or through design thinking related courses that they have taken. None of the participants in this study were familiar with the CAD used prior to this study.

Procedures

In this study, all students were asked to work on a design challenge where they had to build an energy-efficient home by fulfilling a set of requirements provided, using a CAD called Energy3D [12]. Each student was given one and a half hours to complete their design. Each of these students worked on their design individually with the presence of a researcher. While working on the design challenge, students were asked to verbalize their thoughts out-loud (i.e., concurrent think-aloud). The researcher prompted students to talk whenever there was a long silence, as well as answered students' questions whenever there was any. Students' think-alouds were audio-recorded. In addition, students' computer screens where they worked on the design using CAD were also recorded using a screen recording tool called OBS Studio (OBSProject.com – free).

Data Collection and Data Analysis

The data collected and used for this study were: (a) audio recordings of students' think-alouds, (b) screen recordings of students' work on the computer using CAD, and (c) students' final design artifacts. The audio recordings and screen recordings were primarily used to understand the types of uncertainty faced by students, as well as the ways they managed those uncertainties. On the other hand, students' final design artifacts were used to evaluate students' final design performance and its relationship to the ways they managed uncertainty.

The data analysis methods of this study mainly included verbal protocol analysis and video analysis. In order to answers the research questions of this study, the researchers started by skimming through the recordings to get familiar with the data. The researchers also had copies of transcripts at hands whenever they needed to use them. After getting familiarized with the data, the researchers started looking for and documenting "moments of uncertainty" based on both audio and screen recordings. They identified these "moments of uncertainty" whenever students expressed doubts. Once these moments were identified, the researchers categorized them using the categories on the adapted rubric[2], [5], as shown in Table 1 below.

Table 1. Categories of how students responded to uncertainty in engineering design.

Category	Description
Raise	Articulate novel questions or problems, open the problem space, purposefully seek multiple alternative action trajectories or opinions.
Maintain	Delay actions, decisions, or evaluation, acknowledge, or express doubts.
Reduce	Analyze issues, test systematically, engage in trial-and-error experimentation, support or reject claims with evidence; or explain clearly, request information, seek expert help, draw on past experiences, refer to an authority figure.
Ignore	Keep going, avoid, pass off task, dismiss (do not consider introduced uncertainty), or blame.

Once these "moments of uncertainty" were documented and categorized, the frequency of occurrences was calculated to provide a sense of how students tend to respond to uncertainty when engaged in design tasks. Next, again using both the audio and screen recordings, the researchers identified and documented the types of uncertainty faced by students, as well as how they dealt with those uncertainties (e.g., whether using CAD or not). Similarly, the frequency of occurrences was calculated to give a sense of what types of uncertainty did students encountered the most, as well as how did they tend to deal with these uncertainties.

Lastly, using students' final design artifacts, students' final design performance scores were calculated. The final performance score consisted of three major components, which were the final area of the house, the final cost of the house, and the final annual energy consumptions of the house. These components were taken into the calculations because they were the main design requirements that students had to fulfill. Each of these components was scored, and was weighted equally to make up to a 100% score [10].

Trustworthiness

In order to ensure the trustworthiness of this study, the coding was done by two researchers, both having experience in think-aloud protocol and engineering design. To start, the two researchers worked together to develop a rubric that was most appropriate for the data set at hand (i.e., rubric in Table 1). Once the rubric was developed, the two researchers used it to code the data for one student independently and compared the degree of agreement. Once they agreed on the final form of the rubric, the researchers proceeded to code the rest of the data. During the coding process, the researchers would pause and discuss whenever there were doubts, and were eventually able to reach a consensus. The two researchers were able to reach an 88% agreement.

Results and Discussion

The results and discussion of this study were grouped by the three research questions. The results were first reported and discussed individually, and then brought together at the end for a higher-level discussion to provide a big picture of the findings of this study.

(a). What types of uncertainty did students face while working on a CAD-enabled engineering design task?

Through students' audio and screen recordings, five types of uncertainty faced by students were identified while working on a design challenge. These included (a) technical difficulties with CAD – instances when students expressed doubts when CAD was not functioning well, (b) functionality of CAD – instances where students expressed doubts about how to perform a certain action with CAD, (c) design optimization – instances where students expressed doubts about how to optimize the design, (d) design requirement – instances where students expressed doubts about the requirements they need to fulfill, and (e) lack of scientific knowledge – instances where students expressed doubts about scientific knowledge underlying the design that they were not familiar with.

Table 2 below presents the types of uncertainty faced by students and the frequencies of occurrences for each student. Based on Table 2, it is clear that overall, students experience the most uncertainty related to design optimization (i.e., a total of 49 occurrences), followed by the functionality of CAD (i.e., a total of 25 occurrences) and lack of science knowledge (i.e., a total of 19 occurrences). On the other hand, students in general barely struggled with uncertainty related to technical difficulties with CAD (i.e., a total of 2 occurrences) and design requirement (i.e., a total of 2 occurrences).

Taking a closer look at each individual student, it is interesting to see that S6 was the only one who struggled with uncertainty related to technical difficulties with CAD, while S5 was the only one who struggled with uncertainty related to design requirements. In terms of functionality of CAD, S1 and S6 expressed uncertainty with it the most (i.e., 11 occurrences for S1 and 9 occurrences for S6). Similarly, S1 and S6 also expressed the most uncertainty related to design optimization (i.e., 11 occurrences for S1 and 12 occurrences for S6). On the other hand, S2 and S3 expressed the most uncertainty relevant to lack of science knowledge (i.e., 8 occurrences for S2 and 6 occurrences for S4). These results are discussed more under research question (c) when comparing them with students' final design performance.

Since one of the processes in engineering design is experimentation to optimize the design outcome [3], it is not surprising to see that most of the uncertainty faced by students were related to design optimization. In fact, these uncertainties could be beneficial for students learning because uncertainty provides opportunities for students to experiment and argue, as well as to construct knowledge as they design [8], [9]. Similarly, as students experiment when designing, especially for beginning designers, it is expected to see them struggles with a lack of scientific knowledge as well as how to use CAD if they are not familiar, which might be the case for some of the students in this study. What is more important for students, as they face these uncertainties, is knowing how to manage them so that they could be turned into productive learning opportunities.

Table 2. Types of uncertainty faced by students and their frequencies of occurrences. S1 represents student 1 and so on.

Types of uncertainty	**Students**						**Total**
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	
Technical difficulties with CAD	0	0	0	0	0	2	2
Functionality of CAD	11	0	2	1	2	9	25
Design optimization	11	8	8	6	4	12	49
Design requirement	0	0	0	0	2	0	2
Lack of scientific knowledge	0	8	0	6	3	2	19

(b). How did students manage uncertainty while working on CAD-enabled engineering design tasks?

In order to understand how students manage uncertainty while working on CAD-enabled engineering design tasks, this study examined the ways students responded to uncertainty (i.e., raise, reduce, maintain, or ignore from Table 1), as well as how they dealt with those uncertainties (e.g., using what tools?). These results provided not only how students responded to uncertainty, but also how they used CAD or other resources to help them address those uncertainty.

Table 3 below presents the ways students responded to uncertainty and the frequencies of occurrences for each student. Based on Table 3, it is clear that overall, the most common way students responded to uncertainty was by reducing it (i.e., a total of 37 occurrences), followed by maintaining it (i.e., a total of 28 occurrences), and raising more uncertainty or questions (i.e., a total of 23 occurrences). The least common approach used by students was ignoring (i.e., a total of 9 occurrences).

Taking a closer look at each individual, it is interesting to see that S6 had the most identified "moments of uncertainty" (i.e., 25 instances), followed by S1 (i.e., 22 instances), and S2 (i.e., 16 instances). On the other hand, S3, S4, and S5 were the ones on the lower side (i.e., 10 instances for S3, 13 instances for S4, and 11 instances for S5). In addition, it is interesting that S1 and S6 were the ones who approach uncertainty by raising more questions the most (i.e., 7 occurrences for each). Similarly, S1 and S6 were also the ones who tried to reduce uncertainty the most (i.e., 8 occurrences for S1 and 12 occurrences for S6). In terms of maintaining uncertainty, all students seemed to be performing this approach for around the same frequency, with S5 being the exception (i.e., only 2 occurrences). When it comes to ignoring, S1, S2, and S3 were the only students who had instances of ignoring uncertainty (i.e., 3 instances for each). Based on these results, it seems that raising and reducing went hand-in-hand as students approached uncertainty. More discussion on these results is done under research question (c) below when comparing them with students' final design performance.

Table 3. The ways students responded to uncertainty and their frequencies of occurrences.

How students responded to uncertainty	**Students**						**Total**
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	
Raise	7	2	1	2	4	7	23
Reduce	8	4	2	6	5	12	37
Maintain	4	7	4	5	2	6	28
Ignore	3	3	3	0	0	0	9
Total	22	16	10	13	11	25	97

In addition, seven ways of how students dealt with uncertainty were identified. These included (a) ask the instructor – turn to the researcher for help when in doubt, (b) ask questions to self out loud – talk to oneself such as "I wonder why…?", (c) read science handout – read information on science handout provided, (c) change variable using CAD – manipulate variables in doubt using CAD, (d) run analysis using CAD – test design outcomes using CAD, (e) do nothing – ignore doubt, and (f) change variable and run an analysis using CAD – manipulate variables in doubt followed by testing using CAD.

Table 4 below presents the different ways students dealt with uncertainty (whether involved CAD or not) and the frequencies of occurrences for each student. Based on Table 4, it is clear that overall, most students ask questions to themselves out loud when faced with uncertainty (i.e., a total of 30 occurrences), followed by asking the instructor (i.e., a total of 25 occurrences), change variable and run the analysis using CAD (i.e., a total of 16 occurrences), and run the analysis using CAD (i.e., a total of 15 occurrences). There were only small instances where students do nothing (i.e., a total of 6 occurrences), only change variables using CAD (i.e., a total of 4 occurrences), and read science handout (i.e., total of 1 occurrence).

Taking a closer look at each individual, it is interesting to see that S1 was the one who asked the instructor questions the most (i.e., 12 occurrences), whereas S6 was the one who asked questions out loud to himself the most (i.e., 8 occurrences). S2 was the only student who read the science handout to deal with uncertainty, and S1, S5, and S6 were the only ones that changed variables using CAD without conducting an experiment or running an analysis. n terms of running analysis using CAD to resolve uncertainty, S6 used this approach the most (i.e., 8 occurrences). S2, S3, and S5 were noticed for doing nothing at times when faced with uncertainty (i.e., 1 occurrence for S2, 3 occurrences for S3, and 2 occurrences for S5). Lastly, most students had some instances of changing variables followed by running analysis using CAD when faced with uncertainty, except S3. More discussion on these results are done under research question (c) below when comparing them with students' final design performances.

Table 4. The ways students dealt with uncertainty and their frequencies of occurrences.

How students dealt with uncertainty	**Students**						**Total**
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	
Ask instructor	12	4	2	1	3	3	25
Ask questions to self out loud	4	5	4	6	3	8	30

Table 4. continued.

Read science handout	0	1	0	0	0	0	1
Change variable using CAD	1	0	0	0	1	2	4
Run analysis using CAD	2	3	1	1	0	8	15
Do nothing	0	1	3	0	2	0	6
Change variable and run an analysis using CAD	3	2	0	5	2	4	16

(c). How did the ways students manage uncertainty impact their design performances?

In terms of final design performance, results from this study show that all students performed at different levels. Table 5 below presents the performance score for each student. Based on students' performance scores, a level of performance was assigned to each student to ease the process of further discussion by typing results from all three research questions together. Based on their scores, S1 and S2 were grouped as low performance (i.e., 52% for S1 and 59% for S2), S3 and S4 were grouped as moderate performance (i.e., 71% for S3 and 74% for S4), and S5 and S6 were grouped as high performance (i.e., 93% for both S5 and S6).

Table 5. Students' final design performance scores and assigned levels of performances.

Final Design Performance	**Students**					
	S1	**S2**	**S3**	**S4**	**S5**	**S6**
Performance scores	52%	59%	71%	74%	93%	93%
Levels of performance	Low	Low	Moderate	Moderate	High	High

In order to study the relationship between students' design performance and their ways of managing uncertainty while engaged in CAD-enabled engineering design tasks, patterns across results from all three research questions were examined. Table 6 below presents these patterns, grouped by students' levels of performance.

Table 6. Patterns that show the relationship between students' final design performances and the ways they manage uncertainty.

Levels of performance	**Low**	**Moderate**	**High**
Students	S1, S2	S3, S4	S5, S6
Types of uncertainty	• Mostly functionality of CAD, design optimization, and lack of scientific knowledge.	• Mostly design optimization and lack of scientific knowledge.	• Mostly functionality of CAD and design optimization.

Table 6. continued.

How students responded to uncertainty	• All – raise, reduce, maintain, and ignore.	• Mostly reduce and maintain, and some ignore.	• Mostly raise and reduce.
How students dealt with uncertainty	• Mostly ask the instructor and ask questions to self out loud.	• Mostly ask questions to self out loud and change variables and run an analysis using CAD.	• Mostly ask questions out loud to self and run an analysis using CAD.

Based on the patterns found in Table 6, it seems that all students, regardless of their performance levels, expressed uncertainty about design optimization. It is interesting to note that the majority of students who expressed uncertainty related to lack of science knowledge performed either poorly or moderately in their final designs. On the other hand, students who expressed doubts about the functionality of CAD could either performed poorly or excellently.

In terms of the ways students responded to uncertainty, students who performed poorly approached uncertainty in all different ways, including raise, reduce, maintain, and ignore (almost inconsistently). On the other hand, students who performed moderately mainly focused on reduce and maintain, with some instances of ignore, whereas students who performed excellently mainly focused on raise and reduce. In addition, based on Table 3, two students on both ends (i.e., poor performance vs. excellent performance) engaged with uncertainty most frequently (i.e., 22 occurrences for S1 and 25 occurrences for S6). The main similarity between S1 and S5 was that they both focused greatly on raising and reducing uncertainty, whereas the main difference between S1 and S6 was that S1 ignored uncertainty three times while S6 didn't. Intentionally raising more uncertainty can be beneficial to problem-solving by searching for new ideas, following by reducing uncertainty to narrow down the best option [8]. On the other hand, it is possible that ignoring is not the most productive way in dealing with uncertainty (although it depends on the situations), and hence impacts students' design performance. Similar pattern related to ignore uncertainty is observed in S2, and S3 who performed either poorly or moderately because they, too, ignored some of the uncertainty faced.

In terms of how students dealt with uncertainty, results show that students who performed poorly in their final design tend to mostly ask instructors for help or ask questions to themselves out loud, whereas students who performed moderately and excellently mostly ask questions to themselves out loud and use CAD to manipulate variables and run analysis. It is common that when students face uncertainty, one of the things they need is social support, and it can be provided in terms of help from a teacher or peers [8]. In this study, it is interesting to see that students who turned mostly to the instructor performed either poorly or moderately. This could be because compared to other students who performed better, they did not utilize the CAD as frequently to experiment with the uncertainty they faced. This could potentially imply that the role of the teacher is undeniably important; however, it is also crucial for students to directly engage with the problems by experimentation, and in this case, through CAD.

Conclusion, Implications, and Limitations

In conclusion, the results of this study present the different types of uncertainty faced by students while engaging in CAD-enabled engineering design tasks, as well as the ways they managed those uncertainties. Through this study, we showed that the uncertainty framework [2], [5] more commonly used in scientific argumentation, can also be adapted and used in engineering design to study how students manage uncertainty. In addition, we determined that how students responded to uncertainty and the resources they used to help them deal with uncertainty could potentially impact how they perform in engineering design tasks. Specifically, we explored that actively engaging in uncertainty might spark new ideas in students, and when responded appropriately, might lead to productive problem-solving. We also found that CAD seems to be a useful tool to complement a teacher's role in an engineering education classroom by providing students the opportunity to explore and experiment with the uncertainty they face, and when used appropriately, lead to positive learning.

Limitations of this study include the small sample size, as well as the lack of detailed measures in terms of the sequence of how students dealt with uncertainty throughout the entire design process. Future studies should include a larger sample size. It could be beneficial to study the sequence of how students deal with uncertainty at different phases throughout the entire engineering design process. In addition, it might also be interesting to study how teachers introduce uncertainty into engineering classrooms and the effects of that on students' learning.

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