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STUDENTS' DECISION-MAKING IN A PRODUCT DESIGN PROCESS: AN OBSERVATIONAL STUDY

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ABSTRACT

The objective of this study is to investigate students' decision-making during the information gathering activities of a design process. Existing literature in engineering education has shown that students face difficulties while gathering information in various activities of a design process such as brainstorming and CAD modeling. Decision-making is an important aspect of these activities. While gathering information, students make several decisions such as what information to acquire and how to acquire that information. There lies a research gap in understanding how students make decisions while gathering information in a product design process. To address this gap, we conduct semi-structured interviews and surveys in a product design course. We analyze the students' decision-making activities from the lens of a sequential information acquisition and decision-making (SIADM) framework. We find that the students recognize the need to acquire information about the physics and dynamics of their design artifact during the CAD modeling activity of the product design process. However, they do not acquire such information from their CAD models primarily due to the lack of the project requirements, their ability, and the time to do so. Instead, they acquire such information from the prototyping activity as their physical prototype does not satisfy their design objectives. However, the students do not get the opportunity to iterate their prototype with the given cost and time constraints. Consequently, they rely on improvising during prototyping. Based on our observations, we discuss the need for designing course project activities such that it facilitates students' product design decisions.

Keywords: Product Design Process, Information Acquisition, Decision-Making, CAD Modeling

1 Introduction

Existing literature in engineering education has several studies on students' design behaviors in product design processes [1–4]. Such studies have concluded that students, as novices, face difficulties in the problem scoping and information gathering activities of a design process. They lack the design frames to scope their problem and accordingly gather information [1]. Experts, on the other hand, tend to solve design problems from a domain-specific frame of reference which allows them to quickly converge to meaningful design outcomes [5]. Thus, information gathering activities of students require further investigation in order to understand the specific challenges they face in them in order to enable educators to accordingly design courses and facilitate students' design activities.

One of the lenses to investigate students' information gathering activities is by considering design as a decision-making process [6]. While gathering information, students make several decisions such as what information to acquire and how to acquire that information. There lies is a need to investigate such decisions and decision-based design (DBD) frameworks can be utilized to do so [7]. However, the engineering education research community has been dismissive of decision-based design (DBD) frameworks [8]. Dym et al. [8] critique that DBD frameworks provide little guidance on analyzing how students gather information and generate alternatives to make decisions. Moreover, they discuss that DBD frameworks are only considered relevant for making decisions *after* the information required to make such decisions has been acquired [8]. However, we argue that DBD frameworks can be utilized to analyze information acquisition activities of a design process.

Research in decision-based design has progressed to not only focus on artifact decisions but also on information acquisition decisions such as what new information to acquire and when to stop acquiring information [7,9,10]. In our previous work [9], we propose a sequential information acquisition and decision-making (SIADM) framework to understand how humans make information acquisition decisions. The SIADM framework is a decision-making framework that characterizes information gathering activities of a decision-maker as a sequence of information acquisition, information processing, and decision-making activities. In [9], we utilize the SIADM framework to model the impact of problem framing on the outcomes of an engineering design process.

In this study, we utilize the SIADM framework to investigate how students make product design decisions. We focus on their information acquisition decisions such as how to acquire information which ultimately affects their design outcomes. We collect the students' decision-making data through semi-structured interviews and surveys in ME444: Toy Design course offered in the School of Mechanical Engineering at Purdue University.

The investigation helps us draw insights on the specific challenges the students experience while gathering information. We find that they recognize the need to acquire information about the physics and dynamics of their design artifact during the CAD modeling activity of a product design process. However, they do not acquire such information during their CAD modeling activities primarily due to the lack of project requirements, their ability to utilize physics simulation packages, and the time to do so. Instead, they acquire such information from the prototyping activity. With the given cost and time constraints, they do not get the opportunity to iterate their prototype. Consequently, they rely on improvising during prototyping. Our study also supports the observation in existing literature that students, as novices, tend to have higher design iterations than expected in product design activities [1–4]. Furthermore, the SIADM framework enables us to understand how information acquisition activities influence student's decision-making behaviors.

The remainder of this paper is organized as follows. In Section 2, we review existing literature on product design processes. The review explores the themes of information gathering, problem framing, and decision-making including our own work on the integration of these themes. In Section 3, we introduce the course project and its learning objectives. Then, we describe the details of our study including the research methods, data collection, and analyses techniques. In Section 4, we report our observations. In Section 5, we discuss the need to design courses such that it accounts for students' decision-making and information acquisition behaviors. We provide recommendations for the design of design projects and discuss the limitations of this study.

2 Literature Review: Problem Framing, Information Gathering, and Decision-making

Problem framing is recognized as that activity of the design process that deals with the identification of problems, setting the design goals, requirements, and stating the assumptions and/or limitations [1]. Several studies have acknowledged the importance of problem framing [3, 11]. While studying expert designers, the authors [5] observed that the experts engaged in problem framing activities that motivated them to innovate. Studies that focus on expert-novice differences have found that experts spend more time in problem framing activities than novices [1, 12, 13]. Studies on students, as novices, have also shown that students tend to be more effective as designers if they spend greater amounts of time in problem framing activities [14].

Information gathering is an essential part of problem framing activities. Studies have suggested how information gathering is observed in effective team's design behaviors [14]. It is also shown that information gathering as a part of design activities is more meaningful than the act of gathering information in itself [15]. Students who just focused on information gathering got stuck in the early stages of design rather than progressing to generate design outcomes. The authors [15] observe that effective students quickly learn to integrate acquired information within the frame of their problem.

Problem framing and information gathering culminate into decision-making activities [6, 16]. Consequently, decision-based design research has emerged as an important research area built on the foundations of mathematical principles and decision theory [6, 17]. Existing research has focused on characteristics of decision-making activities such as preference analysis [18], decision-making under uncertainty [19], and deviation from rationality [20]. Thus, decision-making motivates the formulation of important learning objectives in engineering design education [21].

Using the foundations of decision theory has been recognized as a means to improve engineering design education [22]. However, DBD frameworks in engineering education are considered relevant purely from a pedagogical standpoint [8]. From a research standpoint, it is argued that DBD frameworks provide little guidance on analyzing how students gather information and generate alternatives to make decisions [8]. Such a belief in the engineering education research community is not unfounded. Historically, DBD research has primarily emphasized on making artifact decisions

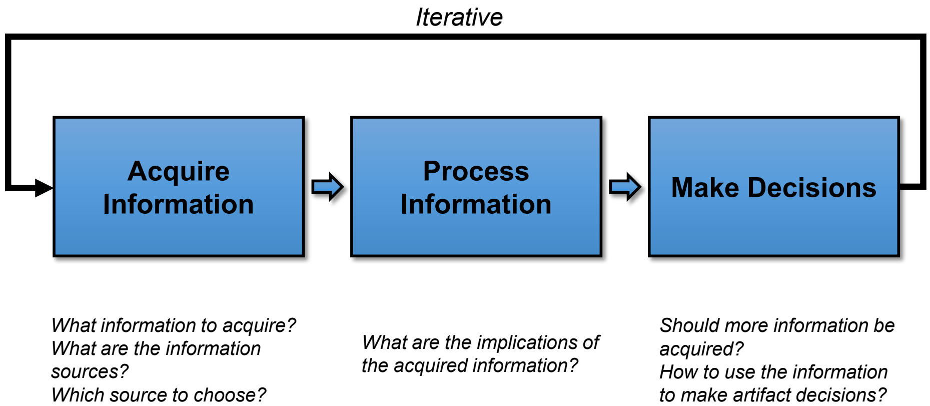

FIGURE 1. A Sequential Information Acquisition and Decision-Making Framework.

using a specified state of information [9]. However, efforts are being made towards utilizing descriptive theory, i.e., understanding how humans make decisions within the design process [7, 23, 24]. In our previous work [9, 25], we propose a SIADM framework that integrates information gathering and decision-making activities.

The SIADM framework is illustrated in Figure 1. The SIADM framework builds on the foundations of extensive research on design activities such as information acquisition, information processing, and decision-making [9]. The framework provides a synthesis of these activities such that design decisions can be holistically analyzed. The SIADM framework focuses on a sequential decision-making process where information is acquired iteratively such that in each iteration the information acquired is utilized to update past beliefs resulting in a new state of knowledge at the end of the iteration. Alternatively, information can be acquired in parallel such that all the information acquired at the end of the process is utilized to generate a new state of knowledge. In this study, we focus on sequential decision-making. Thus, the SIADM framework can be utilized as a lens to analyze the information acquisition activities of students in a product design process.

3 The Study

We observe the students' decision-making in ME444: Toy Design course offered as an elective undergraduate course in the School of Mechanical Engineering at Purdue University. The learning objectives of the course include integrating CAD knowledge with rapid prototyping techniques such as 3D printing and laser cutting. For the achievement of the learning objectives, the students are required to work on two projects, a guided design project and an action toy project. The guided project's emphasis is on CAD modeling and rapid prototyping activities only. In the guided project, they are required to model a car chassis in CAD software and create a prototype. They are provided with all the information required to do so. Thus, they do not engage in information gathering activities. For the action toy project, they are required to design a toy following a typical product design process involving brainstorming, conceptual design, CAD modeling, and prototyping activities. In the action toy project, they experience information gathering and decision-making in various activities of a typical product design process. Thus, our study only focused on the students' decision-making in the action toy project. However, we account for the fact that they gain experience in rapid prototyping techniques via the guided project. Such a design of the course projects was deliberate such that the students have prior experience for the CAD modeling and prototyping activities in the action toy project. The course had a total of 44 upper-level undergraduate students divided into 12 teams. The students work in teams of 3 or 4 who are randomly assigned at the beginning of the semester.

The overview of the activities of the action toy project is illustrated in Figure 2. The students were required to brainstorm toy ideas and then submit a proposal document with detailed design, assembly, prototyping, and purchase plans for two toy design concepts. The project required a "non-trivial motion" and they could make purchase decisions for electronic components such as motors and batteries, if required, with the given cost constraints. The students received feedback on their proposal document from the instructor and the teaching assistants. Each team had to then decide which idea to choose. We consider these activities and decisions as a part of the conceptual design activities for the toy. After the conceptual design activities, the students were required to model the details of their chosen toy in CAD and create the toy assembly. We consider these activities as a part of the CAD modeling activities for the toy. Then, the students had to utilize rapid prototyping techniques namely laser cutting and 3D printing to physically fabricate their toy. They were given size and volume constraints for the same. The students were required to assemble their fabricated parts along with their purchased parts to create the toy prototype. We

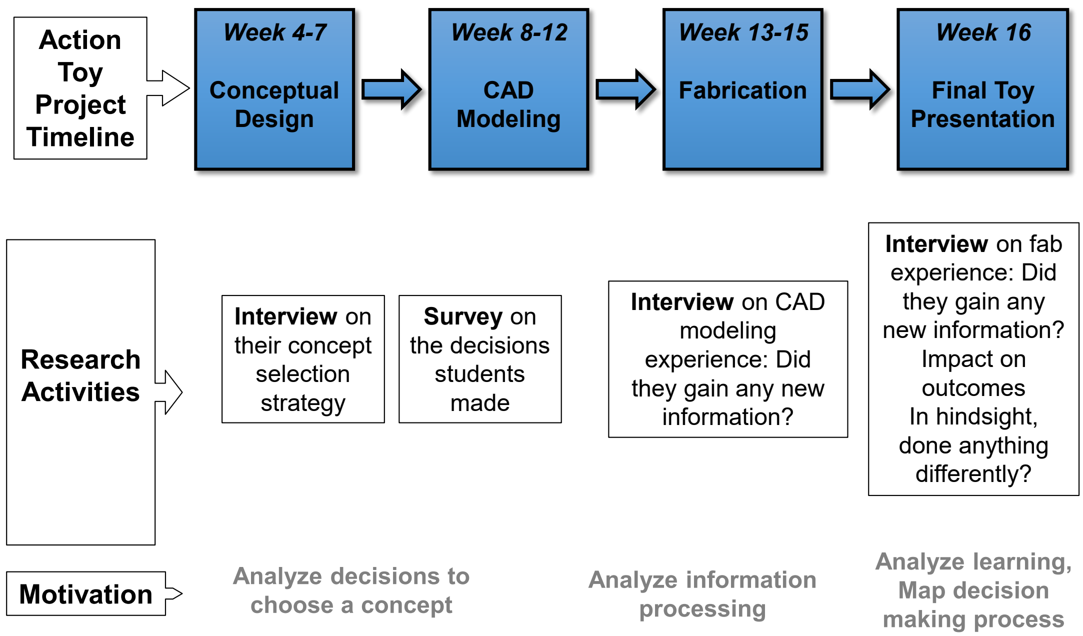

FIGURE 2. Overview of the design process activities and the research activities during the action toy project in ME444 Toy Design course.

consider these activities as a part of the prototyping activities for the toy. Finally, they had to present their toy prototype via a group presentation.

3.1 Data Collection

We conducted one survey and three semi-structured interviews over the course of the toy design project as shown in Figure 2. The survey was conducted during the conceptual design activities and focused on the students having to list the decisions they were making during these activities. The semi-structured interviews were designed to investigate how and why the students made decisions in the conceptual design, CAD modeling, and prototyping activities. The students were incentivized for participating in the survey and interviews. They were provided with a 2% participation bonus to their overall grade.

The interviews were audio recorded and then transcribed. The first and second interviews were conducted one-on-one with the students. This was done in order to document the decisions made by every team member as well as verify decisions across team members. These interviews lasted for an average of 5 minutes. The final interviews (interview 3) were conducted with the entire team due to time constraints and lack of the students' availability after the end of the course. The final interviews lasted for an average of 12 minutes.

3.1.1 Conceptual Design Activities In the conceptual design activities, we focused on investigating the students' concept elimination and concept selection strategy. By the term 'strategy', we refer to their motivations and preferences for eliminating and selecting their reported concepts. We distinguish between concept elimination and selection strategy as follows. We label the students' reported preferences to choose two concepts from the several ideas they were brainstorming as their concept elimination strategy. The students received feedback on their proposed concepts. Then, based on the feedback and their team preferences, they were required to select a toy concept as their toy project. We label the students' reported preferences to choose a concept from their proposal as their concept selection strategy.

The students were asked to complete an online survey and report the decisions they were making, various alternatives they were considering, and the alternative they chose. We use the survey data to report the decisions the students made during the conceptual design activities. During interview 1, the students were interrogated on their strategies to eliminate and select concepts.

We acknowledge that the conceptual design activities are worthy of extensive research on their own. There are several activities that occur at a cognitive level such as students recollecting their experiences from memories which allows them to exploit various known toy concepts as well as students utilizing various sources of information to explore further concepts. However, in this study, for the conceptual design activities, we only focus on the students' decision-making strategy for concept selection and elimination.

3.1.2 CAD Modeling Activities For the action toy project, the students spent the majority of their time on the CAD modeling activities. Therefore, we investigate these activities in detail. From the lens of the SIADM framework, we consider that CAD modeling acts as an information processing as well as an information acquisition activity. CAD modeling enables students to visualize their conceptual design and theref process the information they acquired during design activities. CAD also results in informatio students can experiment with various dimensions and consequently process information about ho will work together as an assembly.

To understand the impact of CAD activities decision-making, we formulate interviews 1 an First, we wanted to know what the students believ a part of the product design activity *before* enterin modeling activities. Since interview 1 was condu beginning of CAD modeling activities, it was u their beliefs. By the term beliefs, we refer to th for CAD modeling such as CAD as an informat activity and as an activity to create STL files t printing. During the CAD modeling activities, th making detailed design decisions such as what choose for each toy part. Interview 2 was co end of these activities. From interview 2, we i students' experience with CAD *after* the activity investigate whether the students acquired additior what decisions they made, and if they encoun unexpected from the CAD modeling activities.

3.1.3 Prototyping Activities During activities, the students assembled the physical pr toy. They had received their parts from the la 3D printing workshops as well as the electronic ordered. Their decisions of tolerance selections for dimensions as well as choosing the fabricating techniques were made during the CAD modeling activities. The students were interrogated during interview 2 regarding their tolerance decisions and their motivation to choose prototyping techniques for their toy parts. During the prototyping activities, they gained information regarding the outcomes of the decisions made in CAD modeling activities.

During interview 3, the students were asked whether they believed that the nature of their design process was iterative and they were asked to elaborate on the specific aspects of what they found iterative in nature. The motivation for such a question was to investigate the sequence of their decision-making process. The students were also engaged in a hypothetical scenario where they were asked if they had added 4 weeks of time, what steps they would have taken. The purpose of such a question was to understand what the students learned from their design prototype and their tendency to move further along the product design process.

3.2 Data Analysis

We analyze teams' decision-making activity from all the interviews as well as the submitted proposal document. These documents were analyzed through content analysis [26] to code

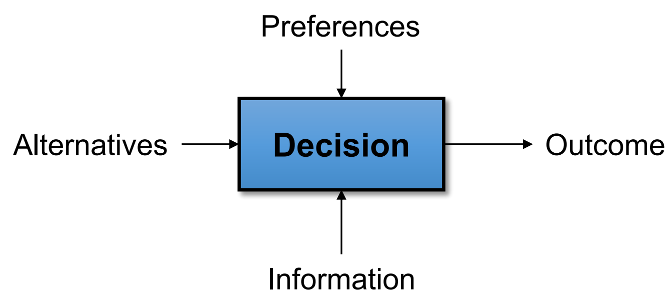

FIGURE 3. Characteristics of a decision.

Using the SIADM framework as shown in Figure 1, we characterize the students' decision-making activity by investigating the information they required to make the decisions, their recognition of whether they possessed the information, their decision to acquire information if needed, and their decision based on the information they acquired. For example, transcripts with words such as "what", "how", "choose", "decide", and "when" typically resulted in identification of decisions. The interviews were semi-structured. Therefore, follow up questions were asked to further investigate how such decisions were made by investigating the characteristics of a decision as described in Figure 3. Various decisions reported by individual students were then pooled to their respective teams to get a clearer picture of their decisions across conceptual design, CAD modeling, and prototyping activities. The decisions in each of these activities are reported in Section 4. We report the common and critical decisions for each team in Section 4.4. In Section 4.4, we also analyze the hypothetical decisions they reported that they would've made from the final interview (interview 3).

For the conceptual design activities, we utilized content analysis [26] to elicit the students' preferences for eliminating and selecting concepts. Through such analysis, we marked words and phrases into various preference categories that represent the

TABLE 1. Concept Selection and Elimination Preferences Coding Scheme

Preference Criterion	Details	Coded Example
Constraint Satisfaction (CS)	Satisfying constraints based on criteria provided in the project description such as complexity requirement, manufacturing techniques, cost requirement, volume constraints, mechanical motion, and complexity.	*"we want to do something with the mechanisms and the ideas that are not feasible with 3d printing and laser cutting [were eliminated]"*
Team's Ability (AB)	Ability to think and execute detailed design for an idea.	*"we all agreed that we wanted to make a mechanism that's simple and it's not outside our ability so the first step was to make sure that everything was doable."*
Team's Interest/Fun (FN)	Whether the concept was fun to pursue.	*"We all picked one idea that we liked that was fun project to make"*
Originality (OG)	Whether the idea was original and innovative.	*"we also wanted our idea to be original and so couple of our ideas weren't original"*
User Centered Design (UC)	Whether the idea was fun for children.	*"we kind of eliminated ideas based on what was the most interesting to kids."*
Fixation (FX)	Selecting an idea because the team was fixated on it.	*"we went and thought about other ideas but since we were most passionate about the first idea we kind of like knew kind of in the beginning that we would go through that one "*
Prior Knowledge (PK)	Whether team members had prior experience to deal with the detailed design.	*"[we] just kinda came up with creative ideas on our own based on the things weve done in our lives "*

conditions on the basis of which the students eliminated and selected concepts. For example, when a student mentioned "we wanted to select an idea that was doable" we considered the statement as a part of their elimination strategy and labeled such a preference criterion as a part of the team's ability category. Table 1 lists all the categorized preference criteria. Such criteria were then utilized to label their concept selection and elimination strategy discussion from interview 1. The transcribed text from Interview 1 was analyzed several times over to count the number of instances that belong to each of these criteria. We sum the frequencies of instances of each of these criteria across interviews. We also sum these frequencies from individual interviews according to the teams to which the individuals' data belonged. Multiple coders analyzed the frequencies to ensure the reliability of the results. The inter-rater reliability (IRR) was calculated by taking the ratio of the number of agreements amongst coders for labeling each instance to the overall sum of agreements and disagreements [27].

$$IRR\% = \frac{Agreements}{Agreements + Disagreements} * 100\% \qquad (1)$$

We also utilized the content analysis to analyze the teams' submitted proposals for their decisions and proposed ideas. The results of the content analysis are presented in Section 4.1. Additionally, the content analysis aided us in understanding the students' beliefs about CAD modeling activity. Such beliefs about CAD modeling are summarized in Section 4.2.

4 Results

We present the results of our observations on the students' decision-making activities in the order of the conceptual design, CAD modeling, and prototyping activities of the product design process as described in Figure 2. We also report our observations from analyzing decisions across individual students as well as the teams.

4.1 Conceptual Design Activities

Out of the 44 students, 34 were available for interview 1. In other words, 7 out of 12 teams had all the members who reported for interview 1. We find that ($IRR\% = 80$) on average the students eliminated ideas predominantly based on constraint satisfaction (CS), i.e., whether the idea satisfied the design constraints provided in the project description. In order to select the final idea, we find that ($IRR\% = 79$) the students not only selected the idea that satisfied constraints (CS) but also selected it based on their team's interest (FN) to pursue the idea. These results are also applicable on a team-level analysis to the 7 teams where all the members reported for interview 1. Table 2 illustrates the frequency count of preference criteria codes for all the teams for concept elimination strategy.

We also find that each team reported two decisions, namely, the decision to propose two ideas, and the decision to select the final idea. However, only two students reported additional decisions related to assembly, prototyping, and purchasing. These decisions were expected to be made while submitting their conceptual design proposal. We observe the students' assembly, prototyping, and purchasing decisions in the submitted proposal document. However, they do not report these decisions in the

TABLE 2. Frequency Count Data for Concept Elimination Coding

Preference Criteria	Frequency of Instances												
	Team 1	Team 2	Team 3*	Team 4*	Team 5	Team 6*	Team 7*	Team8	Team 9*	Team 10*	Team 11*	Team 12*	Sum
CS	0	2	6	16	0	15	7	1	7	3	8	10	75
AB	3	3	2	7	4	0	2	0	2	1	4	5	33
FN	0	4	2	5	1	5	3	2	3	2	1	3	31
OG	0	2	0	1	0	4	1	0	0	0	0	3	11
UC	0	0	0	3	0	0	0	0	3	0	0	0	6
FX	2	2	0	0	0	0	1	0	2	0	0	0	7
PK	0	0	0	1	0	0	0	0	0	0	0	1	2
	'*' indicates those teams where all the members were available for interview 1												

interviews during the conceptual design activities. Instead, we observe the discussion of such decisions during the specific activities for which the decisions were made, namely, during the CAD modeling and prototyping activities.

An interesting observation ($IRR\% = 100$) is that 8 out 12 teams had one of their toy proposal idea similar to the car design guided project conducted earlier in the semester. The idea was modified to accommodate the project requirements, however, it was observed that the students strategize idea proposal such that one of the ideas was an outcome of the brainstorming activity which the team wanted to pursue based on interest. The other idea involved the guided project's car design concepts. This observation is an example of design fixation [28] during the conceptual design activities. However, it can also be argued that the students' design behaviors are rational given the project time constraints such that their prior experience from the guided toy project is being judiciously utilized.

4.2 CAD Modeling

Out of the 44 students, 36 were available for interview 2. We find that 10 out of 12 teams believe that the course content improved their CAD modeling ability as well as their ability to use Creo which is a CAD modeling software. The remaining two teams reported that the course did not improve their CAD knowledge as they already had prior experience. All the students reported that they believe that CAD as an activity is important for the visualization of their design concepts.

We find that ($IRR\% = 100$) 9 out 12 teams recognize the need to model the physics of their toy including aspects such as springs, hydraulic actuators, and gravity. For example, helical springs in Creo can be modeled if one knows how to utilize helical sweeps as well as provide the geometric information required by Creo to do so. However, all the 9 teams reported that they did not acquire such information during CAD modeling activities as the project requirement did not explicitly state the need to do so, the students did not have the appropriate knowledge to utilize various modeling functionalities and simulation packages in CAD, and the students had limited time to fabricate their toy. This resulted in the students encountering prototyping problems as their physical toy prototype did not function as intended. The students also did not have enough resources in terms of budget and time to iterate their prototype. Such setbacks resulted in the students having to improvise modifications for their physical prototype. Table 3 provides examples of instances when the students reported their lack of information acquisition in CAD.

TABLE 3. Examples of instances when the students could not acquire information in CAD.

Team Number	Instance of lack of information acquisition during CAD
Team 6	*"Our design process is definitely iterative because we had to rebuild stuff in cad multiple times and I built 6-7 tracks none of them ending up working the cad model"*
Team 8	*"the physical model was quite different and we had to add multiple batteries and that wasn't accounted for If we had a way to model k value of springs etc it would've been better "*
Team 9	*"the charge system is very tolerance dependent it was difficult to model in cad with motion. our design use a lot of spring based mechanism but its hard to estimate the friction from 3d printed parts "*
Team 12	*"[we] have gravity to worry about and just there is going to be a few problems with how everything comes together"*

We also find that the students report that they execute several design iterations for achieving the volume constraints in CAD. The students experiment with different dimensions of their CAD parts and report this activity as an iterative procedure towards *satisficing* the volume constraint provided for the material utilized for fabrication activities. For example, one of the students reported as follows, *"Our [CAD] design process is definitely iterative because we had to rebuild stuff in cad* *multiple times"*.

4.3 Prototyping

All the 44 students were available for the final interview. We find that the teams' decision to choose dimensions for a toy part was influenced by the prototyping technique chosen for the fabrication of that part. This behavior is consistent with the learning objective of the course where the students are required to learn how to design for manufacturability. We also find that teams who faced difficulty in anticipating potential roadblocks, while translating their CAD model to a physical prototype, relied on trial and error to improve the assembly of their prototype. For example, a member of team 10 reported the following. *"after printing [from] the SLA printer we figured out there was warping 'coz of the print direction. We definitely learnt a lot about improving our design."* .

During the prototyping activities, the students acquired information about the physics of their prototypes such as friction between parts, tolerance limits for 3d printing and laser cutting techniques, the strength of the parts such as springs, and an understanding of the actuation power required for a successful motion of the toy. The students also did not account for the impact of using spray paints to improve the aesthetics of the toy. The spray paint added an additional layer of coating over the parts which resulted in dimension tolerance mismatch and jamming of parts. Such lack of information during the CAD modeling activities resulted in the students reporting the need to have additional iterations during the prototyping activities.

4.4 Decisions

By analyzing decisions across the teams, we tabulated decisions that were common across all teams in Table 4. We also report the decisions that critically affected the design outcome of each team in Table 5. We find that the teams that reported a greater number of detailed design decisions in CAD such as what fasteners to choose, what material to choose, and what parts to order, typically had a functioning prototype. For example, Team 3 reported a total of 16 detailed design decisions and had the best functioning prototype (according to the instructor) whereas Team 5 reported a total of 6 detailed design decisions and their prototype was jamming and did not have a smooth output motion.

During the final interview, all the teams discussed the need to improve their prototype. The students considered the outcome of their design process of the design project as a first iteration of the many required for design prototyping. We also asked them to hypothetically discuss their next set of decisions assuming that they achieved their objectives for all the design activities of their design process. They recognized the need to evaluate the market potential of their product and ultimately discussed the economic decisions required to be made to maximize revenue generation for their product.

It is also noticed that the SIADM framework is formulated in [9] on the assumption that decision-makers optimize for design objectives. However, the students are observed to make decisions that satisfice the design requirements rather than optimize them. For example, when the students are asked why they chose certain dimensions, they typically rationalize their decisions on the basis of satisfying volume constraints. They do not report their decision objective that is to minimize the use of the material. Such an observation is consistent with existing literature on decision-making between experts and novices [29]. In Section 5, we discuss the potential reasons why we observe such a difference between the theoretical SIADM framework and the students' decision-making process.

TABLE 4. Common decisions across teams.

Number	Decision
1	What two concepts to choose?
2	What final idea to choose?
3	How to add functionality?
4	What assembly part to focus on the most in CAD?
5	What manufacturing technique to use for which part?
6	What dimensions to choose?
7	How much volume to assign to each part?
8	How to assemble in real?
9	What material to choose?
10	Which parts to order?
11	How to account for constraints from parts that are ordered?
12	What tolerance limit to choose?
13	How to add the electronics?
14	How to select the best fab model?
15	How to make aesthetic improvements?

5 Summary and Discussion

In this study, we utilize a decision-making framework to analyze students' information acquisition and decision-making activities in a product design scenario. The results of this study paint the following collective picture of how upper-level undergraduate students make product design decisions. We find that during the brainstorming of design ideas, students frame potential ideas on the basis of their prior knowledge and skills acquired in the course, based on design fixation, and on the basis of their domain-specific interests. During the CAD modeling activities of a product design process, we find that the students recognize the need to acquire information about the physics and dynamics of their design artifact. However, they do not acquire such information during these activities. The factors that contribute to the failure of information acquired during the CAD modeling activity are the lack of i) explicit learning

TABLE 5. Critical decisions made by each team.

Team	Critical Decisions Teams Faced
Team 1	How to reduce weight and friction? How many linkages to choose to ensure functionality?
Team 2	How many mechanisms to choose?
Team 3	How to improve strength, usability, functionality?
Team 4	How to simulate hydraulics?
Team 5	How to ensure the complexity required in the project?
Team 6	How to model wires in CAD?
Team 7	–did not report–
Team 8	How to reduce the complexity and sustainability of the design?
Team 9	How to simulate springs?
Team 10	What information to acquire from CAD?
Team 11	How to utilize electronics knowledge?
Team 12	How to ensure innovation requirements?

objectives in the project specifications, ii) the students' lack of knowledge to do so, and iii) the time constraints for project completion. Instead, they acquire such information from the prototyping activity as their toy does not satisfy the design objectives and work as intended. Such information acquisition results in the students wanting to have more number of iterations for prototyping activities to improve the achievement of their design objectives. With the given cost and time constraints, the students do not get the opportunity to iterate their prototype. Consequently, the students rely on improvising during prototyping.

Existing literature has shown that the design of an environment affects user behavior [30, 31]. Students are no different. In the ME444 course, we observed that the resource constraints were a budget limit of $60 and a 15 cubic inch constraint on the volume of material that could be 3D printed. Such constraints in effect implied that the students get one shot to prototype. Thus, the design project essentially abstracted a design scenario where physical experimentation is cost intensive and virtual experimentation is cheap. Consequently, the students' design behavior was observed to be rational where they wanted to gain maximum information from the cheapest information source that is their CAD model and through simulations. Instructors need to anticipate such design behaviors and account for them while formulating design project constraints in the design projects. From a course design standpoint, there lies a need to recognize what aspect of reality is represented by the given design constraints in a design project.

On interviewing the instructor, it was found that they did want to encourage iterations while prototyping. However, due to the lack of additional time to prototype the students could not do so. Instead, the students improvised improvements to their prototype to make them functional without having to fabricate the parts again. Existing studies in design have highlighted the importance of improvisation in product design processes [32]. However, the instructor did not account for such design behaviors. The project was assessed based on innovation, the quality of CAD models and prototypes, their final presentation, and design portfolio. There was a lack of assessment on the team's improvisation to their prototype. By understanding student's design behaviors while acquiring information, assessments of design teams can be improved. Additional studies are required to understand how improvisation in design can be assessed as well as encouraged. We hypothesize that design scenarios where the cost of physical experimentation is high will result in students improvising their design prototypes as observed in this course.

Based on our observations, we recommend formulating design projects such that it guides students towards appropriate information sources as well as accounts for their ability to process the required information. In this study, we find that the course should have been designed such that the students could have the opportunity as well as incentives to gain more information from CAD models, if they wanted to, by teaching them simulation packages or giving enough time in the course for them to develop their domain-specific skills and apply it in CAD modeling activities. However, there was no incentive for the teams who recognized the need to acquire information about the physics and dynamics of their model during CAD activities. Assessments for design projects should account for such recognition of decisions in order to incentivize teams to critically analyze their design. For example, we notice that the students tend to satisfice their volume constraint requirement for 3d printing as opposed to optimize the use of the material. We believe that the students did not have the incentive to optimize such objectives. If the students were given a higher evaluation of their design prototypes if they utilized lesser resources we hypothesize that students would tend to optimize their design objectives as formulated in the SIADM framework.

The authors acknowledge that in practice, it is unreasonable to assume that instructors should possess a "know-it-all" book about all the information students need. Moreover, it should not be encouraged. However, the intent of this research study is to enable instructors to *predict* what information students would need as well as how students would use such information based on their state of knowledge such that design courses can be deliberately designed to encourage information acquisition behaviors.

While existing studies in engineering education highlight that students encounter roadblocks in information gathering activities [1–4], DBD frameworks have not been utilized to analyze their information acquisition decisions. This study illustrates the use of a decision-based design framework for investigating the information acquisition and decision-making activities of students. We highlight the need to integrate information acquisition and decision-making activities. The potential of such an integrated view of these activities can enable us to investigate the factors that influence students' design behaviors. We encourage the engineering education research community to explore DBD research specifically the work on descriptive theories to understand how humans make design process decisions.

Finally, we acknowledge the limitations of our research methods. In this study, we rely on self-reported data from the students obtained through interviews and surveys. In order to verify the decisions reported by the students, we cross-check the reported decisions across individuals from the same team. Students may have self-reporting bias where the rationale for decisions may have been formulated a posteriori. However, the researchers ensured that interviews and surveys were conducted at appropriate instances during the students' product design activities for facilitating recollection of their design activities. For example, we asked the students for their decision-making strategy for concept selection and elimination during their proposal submission to ensure they would be able to recollect their rationale for the elimination and selection strategies. While multiple coders analyzed interviews, a single researcher conducted the interviews. Due to the semi-structured nature of such interviews, we acknowledge that additional data could have been collected if different researchers had variations in follow up questions. Also, although the students were incentivized to participate, the research data is dependent on the amount of information students provide from the interviews and surveys.

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REFERENCES

[1] Atman, C. J., Adams, R. S., Cardella, M. E., Turns, J., Mosborg, S., and Saleem, J., 2007. "Engineering design processes: A comparison of students and expert practitioners". *Journal of engineering education,* ***96***(4), pp. 359–379.

[2] Ahmed, S., Wallace, K. M., and Blessing, L. T., 2003. "Understanding the differences between how novice and experienced designers approach design tasks". *Research in engineering design,* ***14***(1), pp. 1–11.

[3] Cross, N., 2001. "Chapter 5 - design cognition: Results from protocol and other empirical studies of design activity". In *Design Knowing and Learning: Cognition in Design Education*, C. M. Eastman, W. M. McCracken, and W. C. Newstetter, eds. Elsevier Science, Oxford, pp. 79 – 103.

[4] Ball, L. J., Ormerod, T. C., and Morley, N. J., 2004. "Spontaneous analogising in engineering design: a comparative analysis of experts and novices". *Design studies,* ***25***(5), pp. 495–508.

[5] Cross, N., and Cross, A. C., 1998. "Expertise in engineering design". *Research in engineering design,* ***10***(3), pp. 141–149.

[6] Hazelrigg, G. A., 1998. "A framework for decision-based engineering design". *Journal of mechanical design,* ***120***(4), pp. 653–658.

[7] Thompson, S. C., and Paredis, C. J., 2010. "An investigation into the decision analysis of design process decisions". *Journal of Mechanical Design,* ***132***(12), p. 121009.

[8] Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D., and Leifer, L. J., 2005. "Engineering design thinking, teaching, and learning". *Journal of engineering education,* ***94***(1), pp. 103–120.

[9] Shergadwala, M., Bilionis, I., Kannan, K. N., and Panchal, J. H., 2018. "Quantifying the impact of domain knowledge and problem framing on sequential decisions in engineering design". *Journal of Mechanical Design,* ***140***(10), pp. 101402–101402–13.

[10] Chaudhari, A. M., and Panchal, J. H., 2019. "An experimental study of human decisions in sequential information acquisition in design: Impact of cost and task complexity". In Research into Design for a Connected World, A. Chakrabarti, ed., Springer, Singapore, pp. 321–332.

[11] Schön, D. A., 1987. *Educating the reflective practitioner*. Jossey-Bass higher education series, San Francisco, CA, US.

[12] Council, N. R., et al., 2000. *How people learn: Brain, mind, experience, and school: Expanded edition*. National Academies Press, Washington, DC.

[13] Chi, M. T., Glaser, R., and Farr, M. J., 2014. *The nature of expertise*. Psychology Press, New York.

[14] Jain, V. K., and Sobek, D. K., 2006. "Linking design process to customer satisfaction through virtual design of experiments". *Research in Engineering Design,* ***17***(2), pp. 59–71.

[15] Christiaans, H., and Dorst, K. H., 1992. "Cognitive models in industrial design engineering: a protocol study". *Design*

theory and methodology, ***42***(1), pp. 131–140.

[16] Marston, M., and Mistree, F., 1997. "A decision-based foundation for systems design: a conceptual exposition". In CIRP 1997 International Design Seminar Proceedings on Multimedia Technologies for Collaborative Design and Manufacturing, University of Southern California, Los Angeles, CA, pp. 1–11.

[17] Lewis, K., Chen, W., and Schmidt, L., 2006. *Decision Making in Engineering Design*. ASME Press, New York.

[18] Fischer, G. W., 1979. "Utility models for multiple objective decisions: do they accurately represent human preferences?". *Decision sciences,* ***10***(3), pp. 451–479.

[19] Camerer, C., and Weber, M., 1992. "Recent developments in modeling preferences: Uncertainty and ambiguity". *Journal of risk and uncertainty,* ***5***(4), pp. 325–370.

[20] Gigerenzer, G., and Selten, R., 2002. *Bounded rationality: The adaptive toolbox*. MIT press.

[21] Wood, W. H., 2004. "Decision-based design: a vehicle for curriculum integration". *International Journal of Engineering Education,* ***20***(3), pp. 433–439.

[22] Council, N. R., 2002. *Approaches to Improve Engineering Design*. The National Academies Press, Washington, DC.

[23] Hsiao, C., and Malak, R., 2014. "Modeling information gathering decisions in systems engineering projects". In ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, pp. V01BT02A023–V01BT02A023.

[24] Heller, C. M., 2013. "A computational model of engineering decision making". PhD thesis, Georgia Institute of Technology.

[25] Shergadwala, M., Bilionis, I., and Panchal, J. H., 2018. "Students as sequential decision-makers: Quantifying the impact of problem knowledge and process deviation on the achievement of their design problem objective". In ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, pp. V003T04A011–V003T04A011.

[26] Krippendorff, K., 1980. *Content Analysis: An Introduction to Its Methodology (Commtext Series)*. Sage Publications, Thousand Oaks, California.

[27] Miles, M. B., Huberman, A. M., Huberman, M. A., and Huberman, M., 1994. *Qualitative data analysis: An expanded sourcebook*. Sage Publications, Thousand Oaks, California.

[28] Jansson, D. G., and Smith, S. M., 1991. "Design fixation". *Design studies,* ***12***(1), pp. 3–11.

[29] Zannier, C., Chiasson, M., and Maurer, F., 2007. "A model of design decision making based on empirical results of interviews with software designers". *Information and Software Technology,* ***49***(6), pp. 637–653.

[30] Lockton, D., Harrison, D., and Stanton, N. A., 2010. "The design with intent method: A design tool for influencing user behaviour". *Applied ergonomics,* ***41***(3), pp. 382–392.

[31] Rodriguez, E., and Boks, C., 2005. "How design of products affects user behaviour and vice versa: the environmental implications". In 2005 4th International Symposium on Environmentally Conscious Design and Inverse Manufacturing, IEEE, pp. 54–61.

[32] Moorman, C., and Miner, A. S., 1998. "The convergence of planning and execution: improvisation in new product development". *Journal of marketing,* ***62***(3), pp. 1–20.

