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Idea Generation Practices in a Biomedical Engineering Capstone Course

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***Abstract*—*Contribution:* This paper examines ideation practices of biomedical engineering (BME) students in a capstone design course during a designated team ideation session and provides recommendations for structuring idea generation instruction.**

***Background:* Capstone courses provide students with opportunities to engage with open-ended and complex engineering problems requiring knowledge from multiple disciplines. Limited work has focused on how BME students engage in idea generation in capstone courses. Yet, success in solving problems depends on how students engage with and organize their idea generation efforts.**

***Research Questions:* What design activities do BME students engage in during a session designated for idea generation? What factors impact how students approach their ideation sessions and select the ideation approaches to use in a design course?**

***Methodology:* Five student teams were recorded during their idea generation sessions. Post-session interviews were conducted with a subset of students. Qualitative analysis of transcripts revealed themes related to design activities and factors impacting idea generation.**

***Findings:* Students commonly moved into convergent idea evaluation activities during generation. Their approaches to ideation were influenced by course activities and structures, design requirements, and sponsor feedback.**

***Index Terms*—Biomedical engineering, capstone projects, design education, design process, idea generation.**

I. INTRODUCTION

ENGINEERING capstone design courses provide students with opportunities to engage with open-ended and complex engineering problems often requiring knowledge from across multiple disciplines [1]. In biomedical engineering (BME) capstone design courses, students often engage with clinical stakeholders to learn about needs as they design solutions and create prototypes [2]. As with design in any discipline, successful idea generation is critical for innovative outcomes. While design research has broadly explored idea generation within specific fields, BME design research has predominantly focused on collaboration and teamwork [3]. As educational experiences in a specific discipline may be unique, studies of design practices within domains are essential to support improvement in educational outcomes. This work focused on exploring how BME students approached idea generation and course elements that may have influenced their approaches to the design process.

Best practices in idea generation include generating many different ideas, and withholding evaluation of concepts until later in the process [4]–[6]. In practice, students often encounter challenges with idea generation. For example, they struggle to generate multiple and diverse design ideas [7] and fixate on early or existing solutions [8]. While engineering textbooks include some guidelines for idea generation, e.g., [4]–[6], [9], structures and specific instructions have been shown to be lacking in course settings [10].

A variety of factors may direct ideation approaches and influence the types of solutions generated, including: (1) the methods used, (2) the people involved in generating ideas, (3) the nature of the design problem, and (4) the environment in which people are generating ideas [11]–[15]. A variety of idea generation methods and tools exist to guide designers in exploring design spaces, including Brainstorming, [16], Morphological Analysis [17], and *Design Heuristics* [18], [19]. These generation methods can help students explore a broader set of ideas by sparking novel concepts or suggesting transformations of existing ideas [20].

Student team members engage in ideation with support from mentors, coaches, and managers. Within a course environment, people external to the team, such as instructors or stakeholders in the project, can provide feedback that influences how students develop designs [21], [22]. Even with help, there is evidence that the impact of teams on idea generation is mixed. A *process gain effect* [23] can occur, where groups create higher quality ideas than individuals [12], and stimulation from the group can promote additional associations among ideas [15]. However, other studies have found *group process loss*, where individuals are more successful when generating ideas by themselves first [24].

The nature and scope of the problem also influences idea generation; for example, if the problem is narrowly defined or instructions too specific, designers tend to generate few, and not very diverse, ideas [14], [25]. Designers' conceptions of what is practical or useful limits their generation of novel ideas [13]. Clear articulation of the goals of ideation during instruction (e.g., "generate five ideas") has been shown to enhance student success in ideation [25], [26].

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The physical environment, situational norms for practice, and larger organizational structure also impact ideation [11]. Time, place, and technology have been found to be important components [27]; for example, dedicated physical environments can encourage team collaboration and increase idea quality and quantity [27]. In a course environment, students who view design activities as academic exercises [22], [28] show limited use of processes and tools, negatively impacting their idea generation [22].

II. METHOD

The study was guided by the following research questions:

1) What design activities do BME capstone design students engage in during a session designated for idea generation?

2) What factors impact how students approach their ideation sessions and select ideation tools and methods to use in idea generation?

A. Course Context

The study was conducted in a one-semester undergraduate BME capstone design course at a large midwestern university. Upper-level undergraduates and first-year master's students enroll in the course, but the majority are traditionally fourth-year students. Forty-four students were enrolled and worked in nine teams during this study.

In the course, students designed, built, and tested medical devices, informed by interactions with users and stakeholders, including clinicians, industry practitioners, and university professionals. The course design process included four stages: (1) *problem definition*, (2) *concept generation and evaluation*, (3) *detailed design*, and (4) *fabrication and validation*.

The class met twice a week for one hour of lecture and three hours of lab. During lectures, the instructor discussed design process strategies and gave feedback to teams. During the lab, students participated in design reviews, met with stakeholders, and met as a team to work on their projects.

At the start of the semester, teams were assigned to a biomedical design problem. Each project had an industry sponsor and a designated manager (a BME faculty or staff member). Sponsors were experts on the presented problem, and were responsible for providing relevant project information, feedback, and access to specific resources.

Managers were responsible for guiding teams through the design process. During the *problem definition* stage, teams determined design requirements. Students were instructed not to attempt to generate any solutions in this stage.

In the *concept generation and evaluation* stage, students completed a pre-class reading on concept evaluation and the use of Pugh charts. In class, one session focused on idea generation. During the ideation session, students were introduced to brainstorming, where the instructor discussed its value in idea generation, and then taught the *Design Heuristics* ideation tool [18], [19]. *Design Heuristics* are 77 cognitive prompts shown to promote the exploration of multiple diverse ideas [19]. Activities related to the *Design Heuristics* prompts included a short introduction, practice applying several heuristics to a simple problem, questions from students, and time to apply *Design Heuristics* to their problems. During the *Design Heuristics* introduction, the value of multiple ideas was emphasized, but an ideal number of ideas was not defined. Students had the option to attend an additional session dedicated to another ideation tool, TRIZ [29], where they were taught its origins, current uses in industry, and four TRIZ principles: develop statement of ideality, list resources, resolve design contradictions, and separate principles [30]. Students were then expected to complete idea generation with their teams outside of the course meeting times.

For the *detailed design* stage, students presented their top three detailed design concepts and made their final design selection. Finally, students prototyped and tested their final designs in the *fabrication and validation* stage.

Students completed eight deliverables over the term—five written progress reports and three oral design reviews—approximately once every two weeks. One deliverable focused on concept generation. Teams were required to present three distinct solution concepts for their problem. For each solution, students described the layout, unique features, and how each concept would work and be used. They had to articulate the advantages and disadvantages of each concept and justify how they down-selected to a final solution for prototyping.

B. Participants

Participants were involved in two phases of the study—an observation phase where they participated in an ideation session, and a post-session interview phase. Five of the nine design teams participated in the observation phase, representing 25 of the 44 students in the course (13 men, 12 women), one in their third year, 23 in their fourth year, and one in their fifth year of study. The five team projects were:

Team A: decipher tissue layers when introducing a trocar into the body during laparoscopic procedures

Team B: match sleep apnea masks to patients without wasting masks by physically testing the fit on faces

Team C: detect sodium levels for clinical applications

Team D: improve vein ablation therapies

Team E: stabilize the knee externally

Four of the five teams in the study were formed by the course instructor (Teams B-E), based on educational background and student interest in projects. Team A was independently formed based on an existing student project originating outside of this class.

During the interview phase, eight of the 25 participants were interviewed about their idea generation sessions. Interviewees' gender, prior design coursework, and prior design experiences are shown in Table I. Students received $25 for participation in each study phase.

C. Procedures

Ideation sessions occurred after students attended the course idea generation lectures and workshops (Phase 1). For this study, students were asked to conduct their idea generation sessions in a specific room. This space contained whiteboards, a table, chairs, and a video camera. Fig. 1. Students scheduled their sessions over a two-week window, selecting how much

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TABLE I
STUDENT INTERVIEW PARTICIPANTS

Gender	Male	4
	Female	4
Year in School	4th Year	7
	5th Year	1
Previous Design Coursework	Introduction to BME Lab	5
	Introduction to BME Design	6
	Biomedical Instrumentation	8
	Clinical Needs Finding	2
Previous Design Experience	Design Team within a course	5
	Technical Design Internship	2
	"Needs Finding" Internship	1
Student Team Distribution	Team A: 4 (Aden, Brendan, Cai, Devon), Team B: 1 (Era), Team C: 1 (Farah), Team D: 1 (Gail), Team E: 1 (Harper)	

Fig. 1. Idea generation session space provided to student teams.

time they would use for the session. Sessions ranged from one to three hours, averaging 1.5 hours. During the team ideation session, students were video recorded.

In a second phase of the study, students were interviewed about their ideation experiences, approximately one month later (Phase 2). This time between the session and the interview gave students an opportunity to reflect on the ideation sessions and any feedback and to engage in further ideation prior to answering questions about how the ideation session affected their progress on the project.

The semi-structured interview protocol [31] was piloted with three graduate students. Students were asked to discuss the strategies they used in their ideation session, assess how successful it was, other idea generation activities since their team session, and subsequent idea generation efforts. Sample questions from the interview protocol are shown in Table II.

D. Data Analysis

Data were transcribed and reviewed for accuracy. For the first research question, an inductive analysis focused on identifying design activities performed during the session. Next, these activities were compared to design activities documented in engineering textbooks and creative process models [32] and refined. The amount of time students spent in each of the design activities was also calculated for each team. To answer the second research question, patterns were identified in how students described influences on their ideation. To determine consistency, three interviews and three ideation sessions were coded independently by a second coder. Percent of agreement was considered acceptable with 83% for generation sessions and 76% for the interviews [33].

TABLE II
INTERVIEW CATEGORIES AND CORRESPONDING EXAMPLE QUESTIONS

TOPIC	EXAMPLE QUESTIONS
Overview	- What were your team goals for idea generation?
Idea Generation	- Could you describe your idea generation session from beginning to end? - How successful was your team in accomplishing your goals?
Idea Generation Constraints	- Can you describe one thing that you think influenced the approach you used to generate ideas? - To what extent did the previous design stages completed in the course affect how you structured your idea generation session and the strategies used to generate ideas?
Post Idea Generation Session	- How did your ideas and project progress after the idea generation session? - What was the response of your idea from the design review? How did you proceed or how will you proceed after receiving this feedback?
Idea Generation Reflection	- Looking back at the idea generation session, what things would you consider successful about the idea generation session? - What aspects of idea generation could you have improved? - What would you have changed about the process?

TABLE III
CODES DESCRIBING DESIGN ACTIVITIES OF STUDENTS' IDEA GENERATION

DESIGN ACTIVITY	DESCRIPTION
Problem Framing	Determined scope for the project, including target population and boundaries of project
Research	Conducted new research or reviewed previously compiled information
Idea Conceptualization	Created new design ideas individually and/or as a team using idea generation
Idea Development	"Fleshed out" ideas by asking questions, contributing additions, and incorporating technologies.
Idea Evaluation	Weighed the pros and cons of the generated ideas, compared ideas, and identified problems
Idea Selection	Chose their "top" ideas by limiting to one solution type, voting between ideas, highlighting specific ideas as favorites, and narrowing ideas down to a specified quantity.
Other	Engaged in discussions on logistics (i.e., scheduling meetings or timelines) or in non-course related social conversations

III. FINDINGS

A. Research Question 1: What Design Activities Do BME Capstone Design Students Engage in During a Session Designated for Idea Generation?

Teams engaged in problem framing, research, idea conceptualization, idea development, idea evaluation, and idea selection during their ideation sessions, Table III.

All of the teams were observed in all six design activities during their generation sessions, but the amount of time spent and frequency of transitions among them differed by team. All teams cycled between these activities multiple times. If a team generated a higher number of ideas, they tended to cycle through the activities more often than teams with fewer ideas.

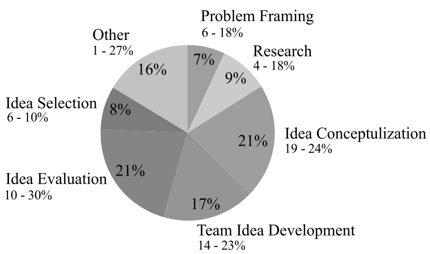

Fig. 2. Average percentage of time the teams spent in different design activities (% in pie segment), and the % range of across teams.

When discussing ideas, teams frequently oscillated between generation and evaluation activities.

The time distribution of activities is shown in Fig. 2. Problem framing, research, idea conceptualization, and idea development activities contributed most to divergent thinking about possible solutions. Teams spent a little over 50% of their time on exploratory activities. Idea evaluation and selection followed as convergent thinking defined by narrowing to an answer. While students were instructed to devote the session to ideation, close to 30% of the session time (on average) was spent on evaluation and selection.

Excerpts from students' sessions demonstrate their activities in the team sessions. These examples illustrate how their discussions addressed best practices in concept generation.

1) Divergent and Exploratory Activities: Students spent approximately 20% of their generation sessions actively coming up with ideas. Many of the teams recognized that quantity was important and raised the need to determine whether they had considered enough ideas, also encouraging their teams to generate more. However, no teams stated a specific quantity goal. Some teams expressed the need to think about ideas other than those they already had, to increase the variety in what they considered. Four teams also made use of Design Heuristics to generate more ideas. Students also elaborated on their ideas to develop more detail and engaged in activities to help them better understand their problem. Finally, the teams explored constraints bounding their problems and solutions. These activities appeared to direct and guide their exploration of ideas.

a) Problem framing: Students used "problem framing" to understand and develop their problem definitions. For example, Team C discussed feedback from a design review indicating that their problem definition was not clear. They reformulated their approach to the problem, saying:

> *"I really think the very first thing we need to do... is find exactly what our scope is... "*

This reformulation of the problem directed the team to consider the user during idea generation, as what patients "would most want" in their solutions.

b) Research: Students engaged in research to establish design space boundaries. For example, Team B used research to structure their idea generation session:

> *"I'll... start out with a half hour discussing the patents and figuring out what exactly our limitations are."*

The team explored limitations of existing solutions to better understand their design space, and then generated new ideas. Across the teams, students consistently used reseach to define paramaters for solutions or suggest solutions based on what already existed. Students also used research to define the parameters of their idea generation and identify possible solutions that could apply to their problem statements.

c) Idea conceptualization: Teams generated or shared ideas. Some teams shared ideas they had already developed, while others used structures to collectively generate ideas. For example, Team A generated categories of ideas based on technologies they discussed during the session.

All teams pushed themselves to generate more ideas during the session. They mentioned the goal of keeping idea generation "*a little broader*" and to be sure they *"brained up what is possible" (Team B).* Some teams mentioned specific goals for developing a lot of ideas. In the post-session interviews, Brandon discussed the goal of creating "*a big list of stuff*," and Gail stated a goal was *"com[ing] up with as many ideas as possible*" while focusing more on *"quantity rather than quality*." Team C repeatedly generated more ideas through statements such as:

> *"Are there any other... big routes we could go down.*"

Other teams also aimed for diversity of ideas:

> *"[They] were coming from it from more angles than what they did before which was good." (Era)*

Farah expressed surprise at her team's success:

> [We were] "*actually [coming] up with a lot of different things, like random things" that were "so out of [their] original scope, but still relevant."*

d) Idea development: During idea development, students built upon the ideas they had previously identified. Era mentioned that his team:

> *"[We] spent a lot of time kind of talking through the different [ideas] and then kind of going off on smaller tangents thinking... where could we expand."*

Idea development was the third most frequent team activity.

2) Convergent Activities: During idea sessions, students did not use the full time for ideation; instead, all moved on to evaluating and selecting final ideas. Teams spent around 20% of their generation session time evaluating ideas. These activities prompted teams to eliminate some possibilities, stop exploring particular avenues they had considered, and choose just a few possibilities before their ideation session ended.

a) Idea evaluation: These activities occurred when students voiced critical remarks about an idea. All of the teams were observed to collaboratively evaluate ideas during their generation session. Sometimes evaluation occurred naturally while engaged in other activities; for example, when a student in Team B was explaining an idea for a device worn on a patient's face, another student interrupted to say:

> *"You want to put all the pieces of thin metal on a patient's face at once and measure at the same time?"*

TABLE IV
REPORTED FACTORS IMPACTING IDEATION APPROACHES

FACTOR	DESCRIPTION	STUDENTS
Course activities	Lectures, direction and feedback from instructors, and assignments.	8
Design requirements	Project parameters deemed necessary by students and/or their sponsors.	8
Sponsor input	Project sponsor's desires and preconceived ideas.	8
Research gathered	Literature or web searches, patents, personal experiences, and products/objects.	8
Limited time in the course	Schedule for project deadlines and structure of team meeting availability for idea generation.	8
Organization of session	How the team structured their idea generation and the extent to which they had an organized approach	8
User focus	Perception of users and their preferences and usability	6

This student had negatively evaluated the idea without allowing the other student to finish explaining it or allowing the team to further develop the idea. Other times, teams intentionally evaluated ideas; for example, Team D proposed:

> *"Maybe we go through every design together and, in one color, write on the board the pros and the cons in another color. We can poke holes in everything."*

While there were several instances of idea evaluation in the generation session, many students did not specifically discuss evaluation in the post-session interviews. This may reflect a lack of awareness of evaluation in their sessions.

b) Idea selection: Overall, teams spent less time engaging in idea selection activities than in other activities. Three teams intentionally selected from their ideas towards the end of the session to find their "*main candidates.*" Team D selected concepts after generation and evaluation:

> *"It feels like [our] main candidates... are the thing that [the team] thought of, this telescoping thing, and then what [they] thought of with the balloon."*

This session ended by establishing consensus on selection.

B. Research Questions 2: What Factors Impact How Students Approach Their Ideation Sessions and Select Ideation Tools and Methods to Use in Idea Generation?

During interviews, students identified specific factors they believed had impact on their teams' ideation, Table IV. They perceived these factors as influential, but did not discuss a positive or negative impact; many were both supportive and limiting to best practices. All but one factor were discussed and observed across teams; the first three were discussed in greater depth because students emphasized these in interviews.

1) Course Activities: Course activities provided "parameter specifics" for students to consider when engaging in an idea generation session. For example, direction and feedback from various project managers (faculty or staff of the BME department or medical school) and design review panelists (biomedical industry professionals and engineering managers) prompted students to consider more ideas and to expand their perceptions of their project scope. Team C was advised by their manager to expand their design space with "completely different methods." This prompted the students to explicitly consider alternative ideas. For example, Cai (Team A) commented on user requirements given to them by their engineering manager:

> *"[We] structured idea generation... to hit these user requirements when we were constructing them."*

The engineering manager instructed the team to incorporate these requirements into their idea generation and concepts.

Six students noted that the *Design Heuristics* lecture was a key factor in their idea generation. Gail viewed the *Design Heuristics* session as an opportunity to "*sit down and think about the project.*" Harper emphasized the value of *the Design Heuristics* session as important guidance: *"without sort of... an impetus from some figure or authority."*

If Harper's team had not done the course's *Design Heuristic* workshop, she felt they *"would've probably blown [idea generation] off or not done it to the same extent."* No teams chose to use TRIZ in their idea generation sessions.

Design Heuristics' were also evident in the generation sessions. For example, Team A spent the beginning of session reflecting upon the *Design Heuristics* lecture and developing ideas from it. This team discussed utilizing ultrasound technology as an additional method to force sensing. Team A generated a "slider" concept using a *Design Heuristic* card. The support provided in the course was observed as a foundation for the students' own generation approaches.

While participating in the study was not required, many teams claimed its structure improved their generation. The sessions were held in an isolated space with fewer distractions to help students focus on generation. Half the interview participants stated that the research study positively impacted their team's idea generation. Gail described the session as more organized and structured than their usual team meetings.

However, other course structures seemed to limit students' generation by directing them quickly towards idea evaluation. For example, Team A established session goals by following the course requirements; since a report was due soon, the team felt it should be their priority. Most teams and students were concerned with meeting the design review deadline, leading their focus away from generation towards evaluation. The course requirements appeared to motivate students towards early evaluation activities in order to ensure they were *"delivering what [the course was] expecting" (Era).*

The ideation tools and course managers supported exploration of multiple ideas as a best practice; however, the concept evaluation grading rubric required teams to present only three different ideas in their design review. This may have encouraged students to move quickly into idea evaluation activities to prepare just three ideas for the review.

2) Design Requirements: Design requirements include features necessary in successful solutions. At times, design requirements led teams to fixate on specific ideas, and pushed them toward early evaluation. For example, Team D discussed requirements throughout their ideation session; for example, spatial dimensions for required units. While members of the team generated ideas, they continuously rechecked the design requirements. Frequently, students reiterated the requirements to ensure another member's idea was in accordance. In a conversation about their sponsor, the team discussed how learning about a sponsor requirement may increase the difficulty of finding a solution:

> *"He tells us that you cannot oblate the vein, or perforate it, or hurt it any way. That would make it hard."*

This team also commented on sponsor requirements at the end of their team session as they evaluated designs based on requirements:

> "*Spring loaded/no electricity needed. I think this, the "no electricity needed" obviously is...This is ideal."*

Throughout the generation sessions, teams considered the design requirements to be fixed constraints. Harper reflected:

> *"We just sort of always had [design requirements] in the back of our mind."*

Era also said that their design requirements:

> *"made [their] idea generation a little bit more narrowed... and harder to do the idea generation."*

Across teams, students reported that this focus on requirements inhibited generation and prompted early and nearly continuous evaluation of ideas.

3) Sponsor Input: Teams were especially attentive to the external sponsor who introduced them to the problem, interacted about needs, and provided feedback. The team's idea generation often focused on sponsors. Gail recounted her experience with her sponsor's previous idea. Though the sponsor noted they were flexible:

> *"He had some kind of an idea of what he wanted to do, so he said that he wants some type of tulip flower, something that like opens and anchors that way... it was in the back of [the team's] mind and [the team] thought about it."*

In addition to attending to the sponsor's ideas, students evaluated their own ideas based on the sponsor's responses. Team C felt their sponsor was not receptive to alternatives, and felt this limited their ideation process:

> "*I think what impacted [idea generation] is what our client wanted... I mean, we really did want to do what our client said, because we like him."*

The team's desire to meet their sponsor's expectations was evident in their idea generation session. Farah described evaluating their potential ideas with their sponsor's perspective in mind:

> *"If it turns out like... the ones that are on the market are not good enough for him, then he really just wants a sodium monitor, then we say like okay, we'll just do it. It's his money. If he's not going to fund anything else... "*

Across teams, sponsor input seemed to prompt students to put the sponsor first, marked by evaluation based on their sponsor's directives.

4) Additional Factors That Impacted Idea Generation: Four other factors that impact the direction of teams' idea generation activities were identified during interviews and observed during generation sessions. One factor was prior research on their design topic. This research provided students with additional ideas to add to their own. Cai discussed how the research allowed *"someone else's knowledge [to be] added on."* Students considered research on existing solutions valuable in their exploration process.

Students were consistently concerned about the amount of time they had left to complete their projects. The looming deadline caused teams to limit the time they spent generating ideas and prompted them to select ideas that were easier to achieve by the deadline. For example, Farah reported that the team:

> *"basically tried to do as much as [they] could in the littlest amount of time... that [was] bad in the end, because [the team] didn't really think of that many ideas. [The team]... didn't take the extra time."*

Students also felt their idea generation was impacted by how they had structured their idea generation activities. Their specific plans both within and following the session structured their available time, as Era noted, to:

> *"talk through the different [ideas] and then go off on smaller tangents."*

Students mentioned idea evaluation as prematurely ending idea generation. Harper's team structured their session:

> *"to come up with [viable ideas] that could continue moving forward."*

Finally, some students emphasized they were mindful of users' needs and how their ideas could address those needs. This prompted students to evaluate their ideas on this basis:

> *"[We] went in with the mentality that nothing was going to be necessarily a good or bad idea, until [they] confirmed it with the patient population." (Farah)*

While the ideation sessions were prominently advertised in the course information, students found that other concerns about the design process interfered with the course plan to provide space and time to consider many, diverse solutions.

IV. Discussion

In the idea generation sessions, students engaged in both exploratory and divergent activities as well as convergent activities. While exploration contributed to their understanding of the solution space, students spent the most time engaged in idea evaluation, along with generating alternative solutions. Similar to the findings of Atman *et al.* [34], generation and evaluation activities did not occur just once in the design process, but were revisited multiple times in the session.

During ideation, some teams set goals to for a large quantity and wide variety of ideas, aligning with best practices [4]–[6], [16]. Students stated the need for a lot of ideas and more time for idea conceptualization [13], [35]. However, the teams' approaches did not always align with best practices because they also continuously evaluated ideas, limiting the number and diversity produced. Prior research notes successful generation is inhibited by evaluation [4], [16].

During idea development, team members built upon each other's ideas. This sharing of ideas can promote generation

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of novel ones [36]. While refining ideas, teams often evaluated them based on their design requirements and preferences. Students sought agreement among team members to direct almost every aspect of the generation session. This consensual approach can result in a single "mindset," that discourages multiple perspectives and limits generation [37].

Six factors were identified by students as impacting the their approaches to generating, developing, and selecting ideas. One of the factors students frequently identified as driving idea generation was the course structure. This included assignments, grading policies, and project deadlines. The design review presentation and written assignment deadlines focused attention on selecting just three ideas. The limited time frame may have persuaded students to engage in early idea selection earlier, limiting time for ideation.

Grading requirements were consistently raised in the generation sessions as an impactful factor in the design environment. Students were driven to meet the course requirements for the design review presentation; thus, their ideation session was aimed at generating the required three ideas. The presence of grading requirements and their desire to earn a good grade drove students to focus on the feasibility of the ideas, an effect seen in other design course research [22], [28].

One activity in the course, the *Design Heuristics* lecture, seeded the idea generation sessions by the student teams. Teams found the method supportive of their design process, consistent with previous studies [12], [13]. This ideation tool provided an opportunity for students to work on their own ideas before sharing them with their team, also known to improve the success of team ideation [24].

While creating and developing ideas, teams focused on design requirements, limiting the quantity of ideas generated and pushing students to consider the most obvious, practical ideas. Of course design requirements must be met [13], [25]; however, ideas may be modified later to align with design requirements.

Feedback from engineering managers also impacted teams' generation sessions. Some managers encouraged students to pursue multiple ideas by generating a large quantity and exploring a variety of beneficial strategies [4]–[6]. More often, teams felt their sponsors led them toward specific ideas. Students were influenced by feedback from sponsors as evaluations of value, as seen in previous studies [11], [22].

Other factors affecting their ideation processes included time constraints, ideation session structures, and user-focused design. Students felt pressure from the course schedule to finish their designs, consistent with findings from previous studies [22], [27], prompting them to move quickly through generation into later design stages. Students also applied some structure to their own sessions by setting goals. Goal-setting is an effective strategy for guiding a session [25], [26]; however, at times, students set goals that were not aligned with best practices.

Finally, some students focused on user needs throughout the ideation sessions, prompting teams to favor concepts they thought would benefit users. Whether these impressions were accurate is not known, but human-centered design expectations [21], [22] did impact the types of ideas generated and explored, and should be considered in future studies. While some research on existing ideas inspired additional student ideas, existing ideas limited generation of other new ideas in some cases.

A. Limitations and Future Work

This study scope was limited to one idea generation session per team; some teams indicated they may not have devoted meeting to idea generation if not part of the study. Instead, ideation would have occurred throughout multiple, short discussions not captured in the study. Future studies could include multiple ideation sessions as well as design meetings not planned for idea generation.

With small qualitative studies, depth of exposure to process comes at the expense of quantity; so, demographics and team dynamics were not be considered as possible influences during idea generation. As a qualitative study, the goal was not to generalize across settings. Studies with diverse teams, courses, and projects can confirm whether these findings are evident in other student engineering teams across a larger sample of the BME field. Further, studies with engineering teams outside of BME may confirm the findings here as applicable across engineering disciplines, students, and courses.

B. Implications for Design Education

Based on the findings, design students may benefit from a more scaffolded approach to idea generation. Design courses can better emphasize best practices by setting up course structures such as deadlines and deliverables to ensure students focus on intended design activities. Course curricula can also emphasize the differences between design phases for idea generation, evaluation, and selection. For example, in this course, a single phase was identified for "concept generation and evaluation." By explicitly instructing students to dedicate time to all three independent phases, instructors may promote a more thorough exploration of the design space during ideation. This could also relieve the perceived time pressure students experience when trying to fit all three stages into one team session.

Instructors can also assist students by providing physical spaces conducive to ideation. Dedicated space and scheduled sessions can support students in following recommended practices for idea generation and encourage students to organize their own activities for idea generation. Without identified time, students may not recognize the need to set their own goals for idea generation.

Other ways to support successful idea generation practices are informed by the factors identified in students' team sessions. For example, instructors should consider the influence of sponsor feedback on idea generation. With this understanding, instructors can facilitate the feedback given to students and encourage sponsors to avoid suggesting solutions. They should also encourage sponsors to support students in considering multiple, diverse ideas in the early stages of design. Finally, understanding the demands on students' time, instructors can consider allocating sufficient time for idea generation, empowering students to fully explore the design space. These factors may not be unique to BME design projects, and should be considered across engineering disciplines.

V. Conclusion

This study explored BME students' approaches to idea generation and identified factors impacting their team design processes. Students engaged in both divergent and convergent design activities during idea generation, and their processes were impacted by course activities and structures, design requirements, and sponsor preferences and feedback.

The students' attempts to manage their approaches to idea generation revealed their heightened awareness of time conflicts, and suggest an opportunity for increased clarity around project guidelines. Though available as guidance, best practices are not always evident in students' actions, and additional structures are needed within courses to promote their use. Because BME is an interdisciplinary enterprise, these findings are likely transferable to these and other disciplines of engineering. Investigations across multiple disciplines can identify additional idea generation approaches to support student engineers as they develop their idea generation skills through design education.

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