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JUNE 22 - 26, 2020 #ASEEVC
Paper ID #29669

Collaboration Patterns and Design Practices in First-Year Project-Based Engineering

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Collaboration and Design Practices in First-Year Project-Based Engineering

Fostering first-year project-based learning (PBL) environments helps to engage students in engineering design practices and broaden their participation pathways in engineering fields [1]. PBL collaborative design activities provide unique opportunities for students to develop, negotiate, and finetune designs. These design activities represent several engineering procedures, from planning projects and improving a production process to developing new materials [2]. However, the collaborative design process in PBL is not well understood. Although researchers have conceptualized engineering design process among engineering professionals [2], [3], [4], [5], few empirical studies have validated these conjectures in PBL. In addition, there is limited research on design decision-making in undergraduate teams. Research on the collaboration structure in PBL has primarily relied on self-reported surveys or interviews; for example, [6], [7]. A limitation to these approaches is that self-reported measures may not capture fine-grained student interactions and provide immediate insights for instructional adjustments.

The purpose of the current study is to examine the collaborative design decision-making among first-year engineering teams. We explored the joint design choices students made, particularly the regulation processes that they engaged in during decision-making. The study has two main contributions. First, it adds to the growing work on operationalizing design decisions within PBL settings. Second, findings have practical implications for instructors to develop scaffolds and reflection opportunities that promote discourse conducive to engineering design processes.

To this end, we employed a comparative case study approach, analyzing team discourse from three PBL sessions to develop a structural representation of each team's collaborative design process (*n* conversational turns = 7,514). The collaboration structures are visualized with Epistemic Network Analysis [8] to highlight the processes and connections among those processes. The resulting networks allow for examination of the differences in team collaboration. We accompany the analyses of the collaboration networks with excerpts from team discussion to illustrate the qualitative differences among groups.

Engineering Design Process

The open-ended design challenges in PBL require students to engage in processes similar to engineering professional practices, namely analyzing the project's functional requirements, partitioning resources and expertise, coordinating tasks, and evaluating results [9]. Arriving at a design decision involves multiple phases, where engineers weigh the risks, affordances, and external influences of each design alternative [4]. The decision-making process may also be iterative, involving feedback loops between understanding the design's function, mapping mechanisms, and creating structure [2]. Due to its complexity, assessment of the design process incorporates not only the final products, but also the steps students go through in scaling problems and seeking solutions.

Researchers have noted patterns in the novice students' design processes. Students tend to offer immediate solutions, as opposed to applying scientific and engineering knowledge to justify for the design choices [10], [11]. In addition, they may become fixated on an idea without generating alternatives or reevaluating their design once they have reached a decision [12]. However, gathering information and refining solutions, as opposed to just building, may assist the acquisition of the fundamental knowledge and skills of the discipline [12], [13], [14]. Engagement in various design processes distinguishes expert from novice engineers. For example, first-year engineering students who spent more time selecting among alternatives produced design solutions of higher quality in think-aloud design tasks [12]. Efficient designers frequently looped through various design stages—gathering information, developing prototypes, and implementation, instead of using a linear process [13].

In sum, evaluating among alternatives is integral to engineering design decisions. Thus, we follow Atman et al. [12] and conceptualize design decision as opting for an idea or solution among alternatives, after a period of brainstorming ideas, modeling solutions, analyzing feasibility, and evaluation. Researchers have used verbal protocol analysis to study the different phases of the design process among undergraduates, graduate students, and designers [12], [13], [15]. These studies applied qualitative coding on the design steps in various think-aloud design tasks. Another approach is to collect students' design reports that outline the problem-solving process or have students critique their peers' design [16], [17]. Scholars have also used observations, surveys, and interviews to capture engineer professionals' perceptions towards and participation in the design processes [2]. However, few studies have applied verbal protocol analyses to examining the design process in PBL engineering teams, where the problem space for design may last for longer durations and involve coordination among team members, in place of just individual regulation of one's own efforts.

Collaboration Process in Engineering

Researchers have proposed joint negotiation frameworks in collaborative design, where task coordination and implementation are interdependent [18]. Successful collaborative design not only requires engineering knowledge and skills; it entails the regulation of goals, beliefs, and behaviors to gear the groups toward task completion at the individual and group levels [19]. Two regulation processes may pertain to the collaborative design decision-making: self-regulation (i.e., individual's monitoring of learning goals) and shared regulation (i.e., coordination and co-construction of group goals and activities towards shared outcomes) [19].

Researchers have explored self-regulated and shared regulated learning in science and engineering settings, for example, [7], [19], [20]. For instance, researchers have examined the self-regulation processes in elaboration, critical thinking, and self-monitoring of one's own understanding [7]. Shared regulation may involve similar processes, namely understanding tasks, setting goals, implementing, and evaluating [21]. Groups with more efficient regulatory patterns may be more likely to engage in frequent and diverse self- and shared evaluation, rather than solely focusing on execution [22].

Findings about regulatory processes parallel the conjectures about efficient engineering designs. Both involve iterations of distinct phases: clarify task, plan for resources and approaches strategically, collaborate and build, monitor progress, and reflect on tasks. However, research on PBL engineering discourse has placed a stronger focus on self-regulation than shared regulation processes [6], [7]. Understanding how students jointly regulate efforts may help to structure collaborative tasks and promote efficient regulatory and design processes—two critical learning outcomes in PBL [1], [7].

Methods

Study setting & participants. The study is part of a series examining the relation between perceived social network and collaboration patterns in engineering design. We followed four first-year student teams in a two-term project-based engineering course in California in the 2018-2019 academic year. The goal of this elective course is to introduce students to fundamental design principles (e.g., Computer Aided Design), concepts (e.g., fluid mechanics, control systems, circuitry, etc.) and skills (e.g. mechanical and electrical fabrication). Each week of the course included two-hour lecture and two-hour laboratory sessions in the first term, and one-hour lectures and two-hour labs in the second term.

PBL was a central component of the course [23], [24]. Students were introduced to how a project developed in full cycle—planning, research and design, manufacturing, and evaluation. In the first term, students were introduced to engineering design fundamentals. Students continued the second term with an autonomous team project, where they applied manufacturing and programming skills to develop a product prototype. Student developed business plans related to their projects and presented their work to the class at the end of the term.

Prior to team formation in the second term, we asked every student in the PBL class to take a survey and report on the peers in the class they would turn to for resources, support, and collaboration, as well as the weekly frequency of contact with those peers. The teams were purposefully selected to represent a range of overall perceived peer support and variation among team members. The sample represents the overall course demographics (22.73% female, 72.72% underrepresented minorities). Table 1 summarizes the teams' characteristics:

Table 1. Team characteristics.

Team	Peer support characteristics	Gender	Race/ethnicity
Team Rise	High peer support. Low variation	2 females, 3 males	2 Hispanic/Latino, 3 White
Team Watch	High peer support. High variation	1 female, 5 males	3 Hispanic/Latino, 1 Asian, 2 White
Team Bone	Low peer support. Low variation	1 female, 4 males	5 Hispanic/Latino
Team Step	Low peer support. High variation	2 females, 4 males	3 Hispanic/Latino, 2 Asian, 1 White

The four teams worked on two autonomous projects. Team Bone and Rise designed an autonomous quadcopter, and team Step and Watch worked on developing a fitness tracker. The decision process over the course of ten weeks for each team was expected to consist of similar principles, concepts, and skills, such as 3D printing and programming. They also consist of parallel regulatory phases, namely understanding design requirements, ideating, planning, building, and evaluation/monitoring.

Analyses draw from the audio transcripts of the teams' discussion (three lab sessions per team; 24 hours of audio data; n = 7,514 conversational turns). A recorder was placed on each team's table for each discussion session, after obtaining student consent through the Institution Review Board. The discussion was audio recorded and subsequently transcribed. Data collection was conducted from the mid-point to the end of the second term. All student names are pseudonyms.

Coding schemes. *Design decision* is operationalized as arriving at a design choice after considering among alternatives [15], [4]. As such, an episode of discourse is coded as containing a design decision if students (a) delineate the design alternatives and (b) provide justifications for their choices. Episodes that misses either of these components are not coded as a design decision. Consider the following example:

> A: When calibrating the y value, we are not going to worry about if the user is raising their hand or what?
>
> B: Yeah, I don't think we have to consider that. I can go ask her [the teaching assistant]. [B came back after talking to the teaching assistant] We don't have to consider regular day to day movements. Just walking.
>
> E: Just walking, okay, cool. It's + or – 150 and anything greater than that is a step. That is what we got from testing. Maybe a little bit greater. We just need to continue testing until we get another parameter.

Here, the students were discussing whether to consider outside movements other than walking in designing their fitness tracker. The design decision on the parameters is reached after consulting external information sources (the teaching assistant) as well as the team's own testing of the device. Student E also indicated potential revisions to the design choices after further testing.

Regulation processes are coded based on the prior literature [19], [21]. The first and fourth author coded 15% of the dataset in several cycles, comparing codes and resolving discrepancies to develop a shared codebook. The codebook consists of two regulation types (self- and shared regulation) and six regulation phases (task understanding, strategic planning, motivation beliefs, control and collaboration, progress monitoring, and reflection). *Task understanding* pertains to the activation of previous knowledge and instruction. *Strategic planning* revolves around consideration of available resources, expertise allocation, timeline setting, and work division. *Motivation beliefs* are individuals or group's feelings about their capabilities and challenges. *Control and collaboration* entail implementation. *Progress monitoring* occurs when students evaluate a solution or the group's progress based on time or goals. Finally, *reflection* usually occurs at the end of the session, when students evaluate the group performance. Examples of regulation processes are provided in the Findings and Discussion.

Validity. The coding for design decisions and regulation processes occurred concurrently. Based on the codebook, the first author and a research assistant separately coded 10% of the dataset for regulation processes, and 25% for design decisions with another research assistant. After reaching substantial agreement (i.e., percentage agreement for identifying design decision episodes per transcript = 93% and Cohen's $\kappa = .81$ for regulation processes), the first author coded the rest of the transcripts. The student and team names were removed during coding to reduce potential researcher bias.

Analytical approach. The unit of analysis is one conversational turn. The researchers first identified the text chunks in the transcript that contain a design decision (n units = 580/7.514 total talk turns). These text chunks were extracted and formatted into an adjacency matrix, such that 1 indicates presence and 0 indicates absence of code for regulatory types (i.e., individual versus shared regulation) and processes. This analysis aims to understand which regulation types and processes signify the collaborative decision patterns of each team.

Next, epistemic network analysis (ENA) helped to analyze the structures of regulation networks of the four teams [8]. Prior research has applied ENA to examine the feedback discourse structure for engineering coaches [25] or the epistemic practices engineering design students engaged in [26]. The unit of analyses for ENA is the codes for regulation mode and process per student per team across the three weeks. The purpose of aggregating for all sessions is to acquire an overview of the regulatory network. Each binary matrix of code occurrences was converted into a vector, and then normalized. This process helps to show the relative frequencies of code co-occurrences regardless of the variation in total units of talks across teams [8]. ENA conducted a dimension reduction algorithm to project the vector on a two-dimensional space (i.e., x and y axes) in ways that best capture variance in the data. The network is weighted, with darker and thicker lines indicating stronger connections that occur more frequently [8]. The position of each nodes suggests the part in which its network has more connections. Analyses were conducted using the ENA web tool [27].

The current study compliments each team's design decision network with illustrative excerpts. The examples present nuances in collaboration patterns, where some teams mainly focused on executing, whereas others engage in multiple processes with iterations within sessions.

Research questions and hypotheses. We explore the following question: **What regulation processes are associated with the team's design decision-making in PBL?** We expect that first-year students who had just learned the basic engineering design concepts and skills would jointly regulate their efforts in creating designs. However, there would be variation in team's engagement in different design processes [14]. The case study was particularly appropriate for documenting potential variation in teams' strategies.

Findings

The number of design decisions varied by teams. On average, teams engaged in 7.00 design decisions per session, with a standard deviation (SD) of 2.59. Team Step made as few as 4.00 decisions per session, SD = .00. Team Watch and Team Rise made as many as 8.33 design decisions per session, SD = 1.53 and 3.79, respectively. Team Bone engaged in 7.33 decisions on average, with SD = 1.15.

ENA provides the design decision structure of each team (Figure 1). The dimensions can be interpreted as follows: the bottom left focuses on regulation types (i.e., self- and shared regulated learning). The bottom right leans towards collaboration. The top left is motivation beliefs and progress monitoring, and the top right is task understanding, reflection and strategic planning. Teams with more connections in the right corner, for example, would be characterized by the regulation of strategic planning, regulation, task understanding, and collaboration.

Teams engaged in different collaboration processes when making design decision. The most frequent interaction is shared regulation of communication and collaboration. This is indicated by the darkest line in each of the team's network between "R.CR" and "C.CC" (Figure 1). Additionally, Team Watch and Team Rise tended to engage in several collaboration phases within a design episode. For example, Team Watch would jointly activate task understanding, collaborate in making sense of the design decisions, and plan for resources in making design decisions (Table 2). The excerpt shows that rather than just collaboration from individuals (i.e., "Collaboration; self-regulate"), the team's discourse was characterized by socially shared negotiation of task understanding, collaboration, and planning.

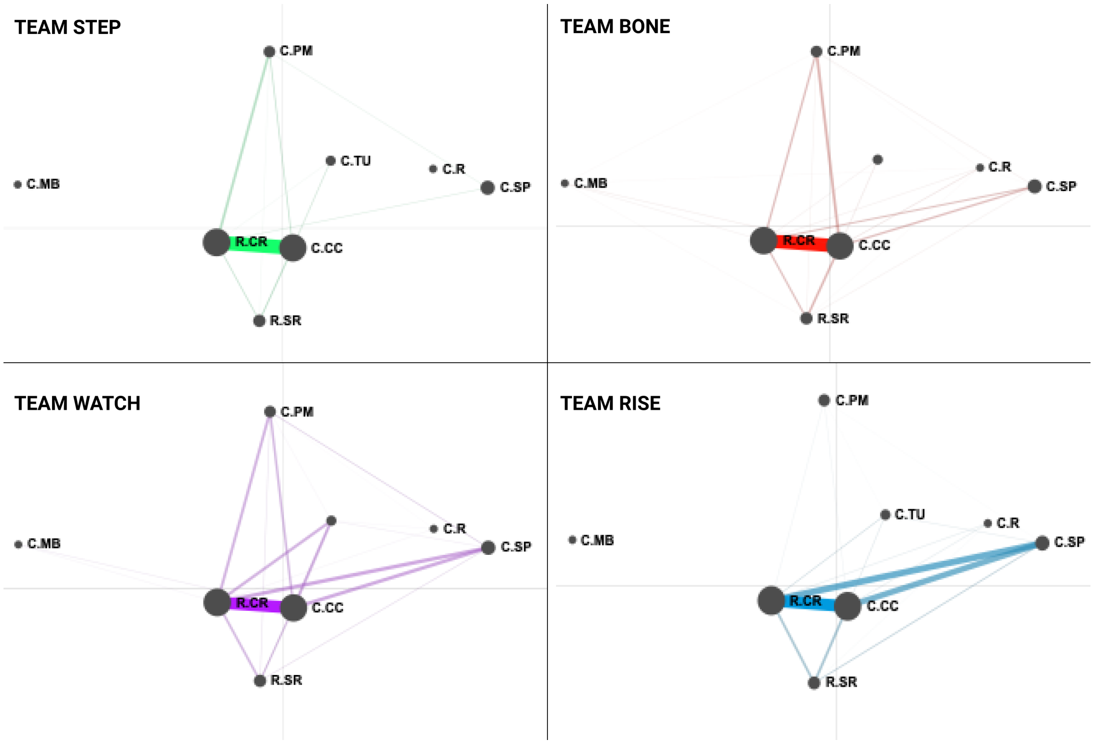

Figure 1. Regulation networks in all design decision episodes for each team. R.SR = Self-regulate; R.CR = Shared-regulate; C.TU = Task understanding; C-SP = Strategic planning; C.PM = Progress monitoring; C.R = Reflection; C.MB = Motivation beliefs; C.CC = Collaboration

Table 2. Exemplary design decision episode, Team Watch.

Phase	Student	Talk
Task understanding, shared regulate	Pat	That's just altitude.
Task understanding, shared regulate	Pat	Cause I know we need steps climbed, but I don't know if we need climb goal.
Task understanding, shared regulate	Pat	Fitness tracking, consistently tracks step count and altitude. Allow for the input of goals.
Task understanding, shared regulate	Mitchel	Of these variables for the app.
Task understanding, shared regulate	Pat	Oh okay.
Task understanding, shared regulate	Mitchel	I think we need both inputs, right?
Task understanding, shared regulate	Bryan	Wait for what?
Task understanding, shared regulate	Mitchel	So, we need, the user should be able to put in a step goal and then an altitude goal. Like an altitude increase.
Collaboration, shared regulate	Anthony	Wait would you phrase it as steps climbed?
Collaboration, shared regulate	Mitchel	Yeah. Steps climbed. End goal or something. Do we need steps climbed on a separate thing?
		[…]
Collaboration, shared regulate	Daniel	Right now, I think it lights up every time that you take a step.
Collaboration, shared regulate	Timmy	Well, yeah that's how we originally had it.
Planning, shared regulate	Anthony	We might want to change that since we don't want it to light every time.
Planning, shared regulate	Ben	For like a floor or flight of steps. Like 16?
Planning, shared regulate	Pat	Yeah, we don't want it to light up. Just when the goal is reached.

In this excerpt, the team was deciding on how to program the step tracking algorithm. Team members first referenced the instruction (i.e., Pat reading aloud the task requirements) and discussed its meaning. Anthony then suggested a design adjustment to change the light-up screen based on the current state of the product and the interpretations of the requirement. This design episode is characterized by even distribution of talk turns among students. Students also appeared to be responsive to the others' reasoning in the shared sensemaking process, as indicated by the dyadic interactions between Pat and Mitchel and the whole team later on.

Similarly, Team Rise's design process often involved several team members. Shared regulation of planning and collaboration marked a number of design episodes from this team. Additionally, compared to the other teams, the relation between shared regulation and planning is more prevalent in Team Rise, as indicated by the thicker blue line (Figure 1). In contrast, Team Bone and Team Step's design decision processes mostly unfolded from building (i.e., collaboration) and progress monitoring episodes. The decision-making process tended to be one-off, with one student initiating and providing rationales for the solutions without returning to those decisions later on as a team.

Table 3. Exemplary design decision episodes, Team Bone versus Team Rise.

Team Bone		Team Rise	
Student	Talk	Student	Talk
Andy	Where is the ball dropping mechanism going?	Charlie	*I thought we wanted to do corner-based sensors, side-based ball drop*
Jake	Good question	Chris	*I was thinking we could have them underside*
Emanuel	Here and here?		[…]
Jake	Does it fit?	Charlie	OK ball drop mechanism again. Are we saying that if the sensors are in the corner, where is this going to be? In the other corner?
Andy	Where is the ball dropping mechanism?	Cam	I was thinking the other corner
Pam	The opposite	Charlie	Just for linear sake, OK.
Emanuel	It's pretty much the right size	Charlie	*If we have 2 different balls then we might want 2 different mechanisms*
Pam	It's going to be bigger	Cam	I was thinking doing it on each corner like one on one corner and one on the other
Andy	It'll fit	Charlie	Wait, one on each corner?
Jake	How about the servo though?	Chris	Like do opposite corners. So, one corner has the servos and the other the ultrasonic.
Jose	Well because there is a nut there though	Cam	Yeah, exactly
Jake	We need to get one of these bad boys to fit in too, that's the thing	Charlie	Somehow attach it and it will work. OK and then the servo.
Andy	Hmm	Cam	We can change the design and make squares
Jake	So, this? Make a hole or something and put it inside	Charlie	How are we going to hold the ball though?
Jake	We can do that, mount it to the, wait actually we have to move the battery, so we can't have anything mounted to it	Chris	**The initial servo is going to be blocking the ball.**
Andy	Mmmmhhh	Charlie	Oh, you're right, OK.
Jake	Let's just make the holes first, we already have the parts. Can you plug this in?	Charlie	**So, the servos will be underneath, all they do is block and then when the time comes it rotates and drops.**
		Chris	Can I see the servo, or one of the servos? I will try to fit them in here.

Text in italic indicates Planning; text in bold indicates Task understanding.

We illustrate the differences in the decision-making among the teams through two excerpts from Team Bone versus Team Rise, where students were discussing the same product feature (Table 3). The excerpt shows how Team Rise appeared to be more consistent in their design with jointly planned arrangement and references to prior decisions. For example, in deciding on where to place the sensors and servos, the team discussed the mechanisms of the servos blocking the ball as well the overall design mechanisms (e.g., "corner-based sensor, side-based ball drop") before jumping into manufacturing. Meanwhile, team Bone's discussion about the design constraints tended to be more surface-level. For example, team members would make observations about the physique of the design parts, as opposed to linking those parts in a comprehensive design scheme. Even when they ran into a design challenge with the battery placement, the team took a trial-and-error approach to creating holes and trying to fit the servos in, rather than reasoning through the feasibility of the design choices or referencing the overall design mechanisms.

In short, ENA and discussion excerpts illustrate variation in collaborative approach to design decision-making. Although teams most frequently engaged in shared regulation of execution, some teams were more likely to employ multiple processes—particularly strategic planning, progress monitoring, and task understanding, while others were more likely to just focus on building. These patterns reflect the coherence in teams' decision process. For example, while Team Rise regularly referred to prior design decisions and overarching design mechanisms, Team Bone did not spend as much time considering alternatives and design refinement.

Discussion

The differences in teams' collective approaches to design decisions provide important insights for how students may orchestrate their own and their peers' efforts in PBL. The patterns about engagement in different design processes resemble observations about expert designers, who are more likely to plan and evaluate, as opposed to novice engineers, who are more likely to build in trial and error [28]. Prior research indicates that engineers who engage in an array of evaluation processes produce higher-quality resultant products [15], [28], [29]. The variation we observed in the final product grades in this study may reflect this observation. The teams who mostly focused on regulating implementation ("C.CC") scored the lowest in the final project score, which is the total of the group presentation and design report on their product. The final score was 93% for Team Watch and Team Rise, 91.5% for Team Bone, and 83% for Team Step. These differences are noteworthy given that teams on either project (Bone/Rise: quadcopter; Step/Watch: fitness tracker) received the same design instruction and attended the same session.

The findings from this study have implications for structuring PBL in undergraduate settings. First, findings suggest that students bring different regulation and decision-making strategies to bear in the classroom. Prior research has found that not every student understands what engineering design entails, which may result in variation in team dynamics and design process [12], [16]. Even though the students in our sample all learned about the engineering project's life cycle in the first term of the PBL course, some may have had more exposure to the design process prior to taking the course. Thus, instructors may consider embedding scaffolds for the design process for students with less experience in engineering design. For example, in addition to the project guidelines, there could be suggestions of the decision processes teams may consider with each project milestone.

Second, there could be short, iterative reflection opportunities at the beginning or end of each session for students to think more comprehensively about the design requirements. Students who were asked to read a design text before solving engineering problems were significantly more likely to spend more time on problem-solving [14]. They also showed more frequent transitions among design steps (e.g., identify need, define problem scope, gather information, generate ideas, conduct feasibility analysis, etc.) and greater consideration of the design criteria [14]. These practices have been associated with the information gathering and evaluation processes that professional engineers engage in [13], [15].

Third, the instructors and teaching assistants could provide suggestions to student teams beyond technical guidance. For example, during progress check-in, the instructors can ask students to recall a design decision they made during the session and evaluate this decision, incorporating several regulation processes (e.g., strategic planning, progress monitoring, task understanding). Based on the team's responses, instructors can prompt for certain design steps for students to reflect more deeply on the design rationales. The extent to which instructors press students to explain their problem-solving strategies is strongly related to the depth in consequent collaborative conversations among students [30].

The current study also has methodological contributions. We illustrate the use of quantitative discourse analysis methods such as ENA to visualize discourse data. Traditional discourse analyses that rely on frequency counts may not examine the structure of collaboration, particularly how regulation types and processes overlap in the design decision process. Our analyses illustrate that even if groups (e.g., Team Watch and Team Rise) have similar design decision episodes on average, their regulatory patterns diverged.

Findings should be interpreted in light of several limitations. First, the case study attempts to explore the different patterns in collaborative engineering design, instead of making generalizations across student populations. Second, the research takes place in a selective public research university. Future research should replicate the study design with other samples in community college, two-year, and four-year private institutions, as well as with other engineering age groups (e.g., high school students) to examine potential variation in group design patterns.

Conclusions

Analyzing design discourse in first-year engineering teams provides a venue to explore students' collaboration patterns in relation to design decision-making. However, prior work has not closely examined the collaborative discourse in PBL engineering to conceptualize the design processes. Findings from this study indicate that student teams took different approaches to design decision-making, with shared regulation of collaborative building being the most prevalent. Teams who were more likely to engage in iterations of regulation processes other than building demonstrated more sophisticated design rationales. Findings have implications for how instructors can structure collaborative learning activities, particularly to provide in-time feedback and iterative reflection opportunities on the design process. Future work includes examination of the differences in learning gains among individuals, by gender and prior achievement. This line of work aims to explore the mechanisms in which students from heterogeneous populations may contribute to design decisions and regulate their own and their peers' efforts.

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