International Journal of Engineering Education Vol. 34, No. 6, pp. 1951–1968, 2018
Printed in Great Britain

0949-149X/91 $3.00+0.00

Investigating the Influence of Context on Students' Self-Regulation during the Capstone Design Course*

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Self-regulated learning or self-regulation is defined broadly as the interaction between the learner, problem, and learning environment. A self-regulated learner tends to be more successful academically. Furthermore, lack of employing regulatory strategies may lead to a failed problem-solving attempt. Research suggests that self-regulation is a recursive, dynamic, complex, and contextual activity. The objective of this research was to understand the influence of contexts in students' engineering design process during a Capstone design course. We recruited two groups, 18 students in total, from the Biological Engineering Department and another two groups from the Mechanical and Aerospace Engineering Department at Utah State University, USA. All groups were working in a fully funded senior Capstone design course. We collected and analyzed various qualitative data using Dym & Little's design process and Butler & Cartier's self-regulation frameworks. The primary qualitative data, which was from the participants' design journal, were segmented and coded by four engineering designers. Our findings suggested that the participants' self-regulation during the design process was influenced mainly by the nature of the design process itself, the nature of the project in the respective discipline, and the participants' experience.

Keywords: self-regulation; design process; in-context strategies

1. Introduction

When dealing with an ill-structured problem with multiple possible solutions such as design, students must be able to set reasonable goals in order to tackle the problem strategically. They must engage both problem-solving skills as well as self-regulation skills. Numerous studies have reported that self-regulation skills are essential during a problem-solving enterprise [1–11]. Further, because self-regulated students are typically aware of their thinking process, they tend to be more successful academically [12, 13] and to produce higher quality design [14], and may develop into individuals who view learning as an ongoing, lifelong process [15, 16]. While self-regulating, students consider the given task and various contexts surrounding the task [17–19], in such the contexts of a problem influence their self-regulation [20–22]. Unfortunately, there is limited literature regarding the influencing context of the discipline [23].

Unlike other studies that focus on students' design strategies, the objective of this research was to better understand the influence of contexts during a design enterprise in a Capstone design course. The course was selected because it provided a rich, authentic learning environment that could foster students' self-regulation skills. By assessing students' self-regulation activities, we identified the primary influencing contexts that shaped their engagement. The findings of this study are expected to expand the limited knowledge in this area and help course instructors to better improve students' self-regulation skills.

2. Engineering design and capstone design course

Engineering design is an iterative process [9] to identify the most suitable components and procedures to meet a client's needs and constraints [24]. In an industrial setting, a design process also includes managerial activities [25], such as the management of the team, design activity, design scope, quality, risk, schedule, budget, and resources [9], [26–29]. The primary goal of such managerial activities is to ensure the project's success by balancing the budget, schedule, and design scope [9]. Additionally, an excellent project management activity could accelerate the design process by reducing the number of design iteration between tasks [30].

In some cases, managerial and design activities overlap, for example: developing and revising a project's work breakdown structure (WBS). The WBS is a "product-oriented family tree that identifies the hardware, software, services, and all other deliverables required to achieve an end project objective" (p.2) [31]. From a design standpoint, the WBS serves as a method to decompose a complex design problem [32]. From the management perspective, the WBS is useful to identify design tasks, assign people to each task, and track the design progress [32].

Due to its complexity, educators have developed

* Accepted 20 June 2018.

various models of the design process [33], such as phase-based, activities-based, solution-oriented, problem-oriented, abstract, and procedural models. Of these variations, we prefer the phase-based models because they are considered to be the best approach to assist students in understanding the complexity of the design process [34]. There are countless phase-based models in the literature. Most of them characterize the design process as a complex activity, which includes: understanding the problem, generating design ideas, evaluating the generated ideas, selecting the most relevant and feasible design, modeling and analyzing the chosen design, detailing the selected design, and communicating the design [9, 26–29, 35–37]. Among them, we selected Dym and Little's model [9] to frame this study for three reasons. First, this model captures the similarities of most phase-based models in its five design phases, which are the problem definition (PD), conceptual design (CD), preliminary design (PYD), detailed design (DD), and design communication (DC) [9]. The model describes that the design flows from the PD phase to CD phase, and then to the PYD phase, DD phase, and the DC. If designers detected an issue from the previous phase, they may return to that phase and address the issue [9]. Second, the model provides specific design strategies for each phase, which is beneficial as supplementary instructions for the students and as a codebook for the researchers. The codebook is "a compilation of the [qualitative] codes, their contents description, and a brief data example for reference" (p.21) [38]. Table 1 presents Dym and Little's definition and specific design strategies for each phase. Third, the model views project management as an integral part of the design.

In the industry, engineers must work in a group setting [25] where each member assumes at least one role [39]. They must learn about each other's strengths, and utilize their full potential. The team members' ability and work ethics will influence the solution's quality and time delivery [40]. Being able to deliver a quality product promptly is key to any engineering businesses; it is the foundation of a good project management activity in the industry [6, 41]. Naturally, equipping students with positive managerial skills is imperative. In this study, we focused on the team, time, and resource management activities. Studies suggest that having skills in these three managerial aspects is necessary for an efficient engineering team [42, 43]. Table 2 presents the definition of these management aspects according to Dym and Little's model [9].

Industries need engineers who can apply the basic science and engineering knowledge during the design process [44]. In response, most higher educa-

Table 1. The definition of all Design Phases and the Associated Design Strategies

Design Phase	**Design Strategies**
Problem Definition (PD): Framing the problem by clarifying the client's objective and gathering the information needed to develop an unambiguous statement of the client's wishes, needs, and limits.	1. Clarify design objectives. 2. Establish metrics. 3. Identify constraints. 4. Revise problem statement.
Conceptual Design (CD): Generating concepts or schemes of design alternatives or possible acceptable design.	1. Identify the design function. 2. Generate design alternatives. 3. Refine and apply metrics to design alternatives. 4. Choose a design.
Preliminary Design (PYD): Identifying principal attributes of the chosen design concept or scheme.	1. Model and analyze chosen design. 2. Test and evaluate chosen design.
Detailed Design (DD): Refining and optimizing the final design and assigning and revising the design details.	1. Refine and optimize chosen design. 2. Assign and Fix design details.
Design Communication (DC): Documenting the fabrication specifications and their justification for either the prototype builders, customers, managers, manufacturers, or other stakeholders.	Document the final design.

Table 2. Project Management Aspects and its Definitions

Activity	**Definition**
Time	Monitoring and overseeing the time planned and allocated to complete the design project.
Team	Administrating and overseeing teammates at the fullest extend to produce a quality of design process and outcomes.
Resource	Administrating and overseeing resources available at the fullest extend to produce a quality of design process and outcomes.

tion institutions require their senior students to take the Capstone engineering design course before graduating [45, 46]. During the one- or two-semester course, students will hone their design and management skills by solving real-world design problems in varying degrees of complexity [46–49]. Typically, the design problems are provided by clients from industries or individuals [47]. The problems are typical design challenges which have a vague goal statement, incomplete objectives, and few constraints [48]. This design problem solving experience enables students to practice and carefully apply both relevant theoretical and hands-on skills to solve real-world challenges [50]. The design deliverables include a design proposal, schedule, design journal, presentations, detailed design schemes, and a prototype of the proposed design. During the course, students will not only learn about coping with the design complexity, but also the art of balancing the tasks and powers distribution among the team members [51], which is a significant learning process [52]. After the course, students tend to be more confident in their hard skills [53–56].

3. Self-regulated learning

Similar to any problem-solving activities for a complex and ill-structured problems, solving a real-world design problem requires focus and monitoring in an iterative manner [9, 16, 47]. In educational psychology, an intentional, continual, iterative, and circumstantial activity to control one's thinking while engaged (i.e., self-regulation) in learning activities is called self-regulated learning (SRL); both terminologies are used interchangeably in this paper. Thus, this study uses self-regulation to refer to students' intentional, deliberate control of thoughts, feelings, and actions to complete the given design problem [57, 58].

Using Butler and Cartier's SRL in-context model, this study frames students' self-regulation during the design process as the interactions between the students (i.e., their knowledge about the discipline, self, and experience), the design environment (i.e., the design problem, resources, and feedbacks), and students' iterative and continuous engagement with the design environment including the strategies they used to solve the problem, and emotional and motivational engagements [20–22]. Specifically, we are interested in identifying students' task interpretation (TI), planning strategies (PS), enacting strategies (ES), and monitoring and fix up (MF), which is also known as the strategic actions [20–22, 59–61]; see Table 3 for the definitions of those strategic actions.

Comprehending the contexts surrounding a self-regulating action is an important step to understand and interpret it. The term *context* refers to all facts and conditions associated with a particular action or instance [17, 18]. Since different contexts stimulate a unique self-regulation response, the details of the context are important. In a design project, for example, engineers employ different strategies when managing the project and when developing the most suitable design for the given problem. It is important to note that a self-regulating activity might not only be influenced by just one context but multiple layers of contexts [59].

To integrate the design process and SRL concepts requires the ability to recognize the subtle differences between the student's intention and understanding the task (TI), making a plan to solve the task (PS), enacting the plan (ES), and checking and adjusting (MF) the outcomes and process. For example, during the problem definition phase, the primary objective is to understand the design problem, specifically, to determine the design goals, functions, and constraints [9]. When students think that they need to determine the design goals, they are interpreting a design task (TI). When they plan to read the design description or brainstorm with the team to identify the design goals, they are engaged in a planning activity (PS). When they read the design description or brainstorm with teammates, they are engaged in the enactment activity (ES). Similarly, when they make and review the meeting notes to ensure the accurateness of their understanding, they are engaged in the monitoring and fix up activity (MF). Naturally, these activities may occur as needed, and new self-regulatory strategies may be added as necessary.

Table 3. Definition of each Strategic Action in the Self-regulating Process

Strategic Action	Definition
Task interpretation (TI)	Students' understanding about relationships between task characteristics and associated processing demand [89].
Planning strategies (PS)	Selecting appropriate cognitive and metacognitive strategies for completing any tasks [59].
Enacting strategies (ES)	Students' cognitive activities employed as they engage in their work executing the design tasks, as planned, monitored, and adjusted through metacognitive activity (i.e., self-regulating strategies) [14].
Monitoring and fix up (MF)	Students' activities of self-monitor progress (monitoring) and adjust goals, plans, or strategies based on self-perceptions of progress or feedback (adjusting approaches to learning) [59].

Studies have found that during the design process, students are highly skilled at applying various task interpretation strategies, but are less skilled in selecting proper planning, enacting, monitoring, and adjusting strategies [14]. Studies also reported that students employ various design and cognitive strategies during the design process at varying levels of intensity [4, 5, 15] and proficiency [14]. Another study reported that male and female students self-regulated differently during a design project [15].

4. Research participants

Two groups from the Biological Engineering (BE) department and two groups from Mechanical and Aerospace Engineering (MAE) department at Utah State University, USA were recruited as participants. All members of the groups were high-performance, senior students (i.e., with GPA of 3.00 to 4.00 on a 4-point scale) who were enrolled in the Capstone design courses and worked on four different and fully funded engineering projects. Their clients were either from an industry or a research institution. The study participants consisted of 16 males and 2 females, and all were Caucasian with the exception of one Asian.

The BE groups 1 and 2 (i.e., BE-G1 and BE-G2), were studied for 36 weeks, and the MAE groups, MAE-G1 and MAE-G2, were studied for 13 weeks. Some BE participants were inactive for few weeks due to personal agendas, such as participating in an internship program. Data collection of the BE groups began after they had formed the groups and finished their project proposal (i.e., defining the design problem), while the MAE groups began directly after they had formed their groups. Consequently, we did not compare all groups' self-regulation during the problem definition phase. Although the BE and MAE groups were not enrolled in the same Capstone design course, they had similar assignments; for example, they were required to submit a design proposal, weekly report, final design report, and design presentation. All groups could utilize any available resources at the university, including the computer lab, bio-engineering lab (mostly for the BE participants), meeting room, discipline-specific experts, and library.

The objective of the BE-G1 project was to lower the production cost of antimicrobial peptides by using Escherichia coli in the cloning process. The antimicrobial peptides were useful as innovative antibiotics that could counteract strong bacteria (i.e., impervious to common antibiotics). Although various plants and animals naturally produce these peptides, they are not widely used in the pharmaceutical industry due to cost issues. In this project, the group's activities included constructing the antimicrobial peptides expression system, fermentation, activity analysis, purity analysis, yield analysis, and yield optimization.

The objective of the BE-G2 project was to develop a drug delivery system for patients with abnormal liver or kidney function. It is commonly known that compromised liver or kidney function reduces the patient's ability to consume a normal dose of most medications safely. By utilizing human serum albumin as a carrier, a smaller concentrated dose of medicines can be injected into the target area. In other words, it is more effective and safer for the patients. This project required the group to identify the drug binding and releasing methods, to design a programmable device for injecting the drug, and to conduct in-vitro tissue testing of the system.

The objective of the MAE-G1 project was to help a semiparalyzed client to use a standard residential bathroom facility freely. The client's comfort and safety were the group's highest priorities, especially given that the target environment was humid. Additionally, their design was to allow the client to use the facility safely during a power outage. Due to its potential usefulness, a universal design that could accommodate anyone in any bathroom setting was preferred. This project required the team to design a body support and attachment, structure, motor and control mechanisms, and power system.

The objective of the MAE-G2 project was to design a low-cost, motorized wheelchair attachment for potential older adult users in the U.S. and India. The design was to be easy to be installed and used by anyone from both countries. Consequently, one of the project challenges was complying with the safety standards from the two countries. This project required the group to design the power, control, and propulsion systems, and assist structure.

5. Research design

As suggested by numerous researchers [14, 15, 59, 62–65], the current qualitative case study used multiple assessment methods to investigate students' self-regulation during an engineering design process. We collected various data from the course management system, e-Journal (eJ), written interviews, design journey, and shared cloud storage. Several studies have suggested that collecting multiple, in-depth data is the gold standard for conducting self-regulation research [59, 66, 67]. One research question guided the data collection and analysis method: How did various contexts influence the participants' self-regulatory approaches during working on a design project?

5.1 Data collection method

The eJ was developed by reconfiguring and extending the Redmine's, which is an open source project management system [68], functionalities. We drew upon Dym and Little's [13] and Butler and Cartier's model [10] to adjust and develop the flow of the system. The eJ allows participants to store and organize their design plans, journals, artifacts, and expenses [69]. Additionally, it allows the participants to receive updates and access the design progress anytime and anywhere [69]. To reduce potential technical problems related to the instrument, we organized a workshop prior to the data collection, provided online materials, and opened up two communication channels. In the workshop, we demonstrated and discussed the workflow, features, benefits, and potentials of the eJ. In addition to the training, the workshop material, eJ Manual, and Redmine online manual were always available in the eJ. Two communication channels were available: email and a face-to-face meeting at the researcher's office. Unfortunately, even though the participants used the eJ, they did not fully utilize it throughout their design process, and merely used it to report their design activities to us.

The participants' used Canvas^{TM} as their course management system. Canvas^{TM} is widely used in K-12 education, higher education, and business institutions [70] due to its flexibility and customizability [71]. Using this course management system, we obtained the course schedule, assignment descriptions, participants' submitted assignments, and participants' grades. The written interviews consisted of eight open-ended questions to assess the participants' perception of and self-regulation during their design and management activities. For example, the participants were asked to describe three successful or unsucessful experiences related to their design process or teamwork. The questions were all answered by the participants. The design journey map is a tool to help the participants chronologically describe their design experiences, including their emotional, design, and teamwork challenges. This technique was adapted from a qualitative study on graduate students' experience [72] and engineering dropouts [73]. We collected the design journey map and narration from all participants. We also collected qualitative data from the participants' Google Drive and Box cloud storage systems because they utilized these services to share various data (e.g., design documentation, analysis, and 3D models) with their team.

5.2 Data analysis methods

The primary qualitative data analysis revolved around the participants' eJ entries. Fig. 1 presents a sample entry from MAE-G1. A journal entry consisted of the reporter's name, collaborator's name, date, time, activities, time spent, and attachments (e.g., design artifact). The eJ analyses included entries verification, design process segmentation and coding, SRL segmentation and coding, frequency counting and analysis, process flow development and analysis, WBS identification, segmentation, coding, and process flow development and analysis. Each activity had a different focus and goal. During the analyses, we triangulated the primary qualitative data, findings, and interpretations with other collected qualitative data. Additionally, we compared our findings and interpretations with existing literature related to the engineering design process and self-regulated learning.

The eJ entries were contextual and process-sensitive. Having the knowledge about the groups' disciplines was necessary in order to understand the entries. In that respect, we recruited four experts, two from each discipline (i.e., BE and MAE). These experts were male and had been involved in various research and engineering projects within their discipline. They verified, segmented, and coded all eJ entries generated by the groups from their respective discipline.

The eJ entries were verified by confirming the authenticity and plausibility of the recorded activities against the design artifacts, other collected qualitative data, and verified entries. Verifying the eJ entries against other qualitative data was necessary because sometimes the participants did not report their activity into the eJ, but rather stored the results (e.g., design artifacts) in the cloud storage or course management system. The experts verified 83.02% of 212 entries, and then focused on the remaining analyses of the verified entries.

The experts independently segmented and coded the verified entries based on Dym and Little's design phases, design activities, and project management aspects. There were 22 predefined codes, as shown in Tables 1 and 2. We provided the experts with the definition of each code and organized a practice session. After 3 to 4 weeks, the experts and one of the researchers met to discuss and resolve any disagreements. During the discussion, the experts agreed to add a code (i.e., "other") for describing some activities related to preliminary design, design communication, and project management. The additional code was necessary because the identified segments could not be grouped into existing design activity codes (e.g., modeling and analyzing chosen design), such as following a specific procedure or a general managerial activity. The experts agreed ultimately on 2301 code-segments with an average Kappa score of 0.99, which can be interpreted as an almost perfect agreement [74].

The verified eJ entries were also segmented and coded based on Butler and Cartier's strategic

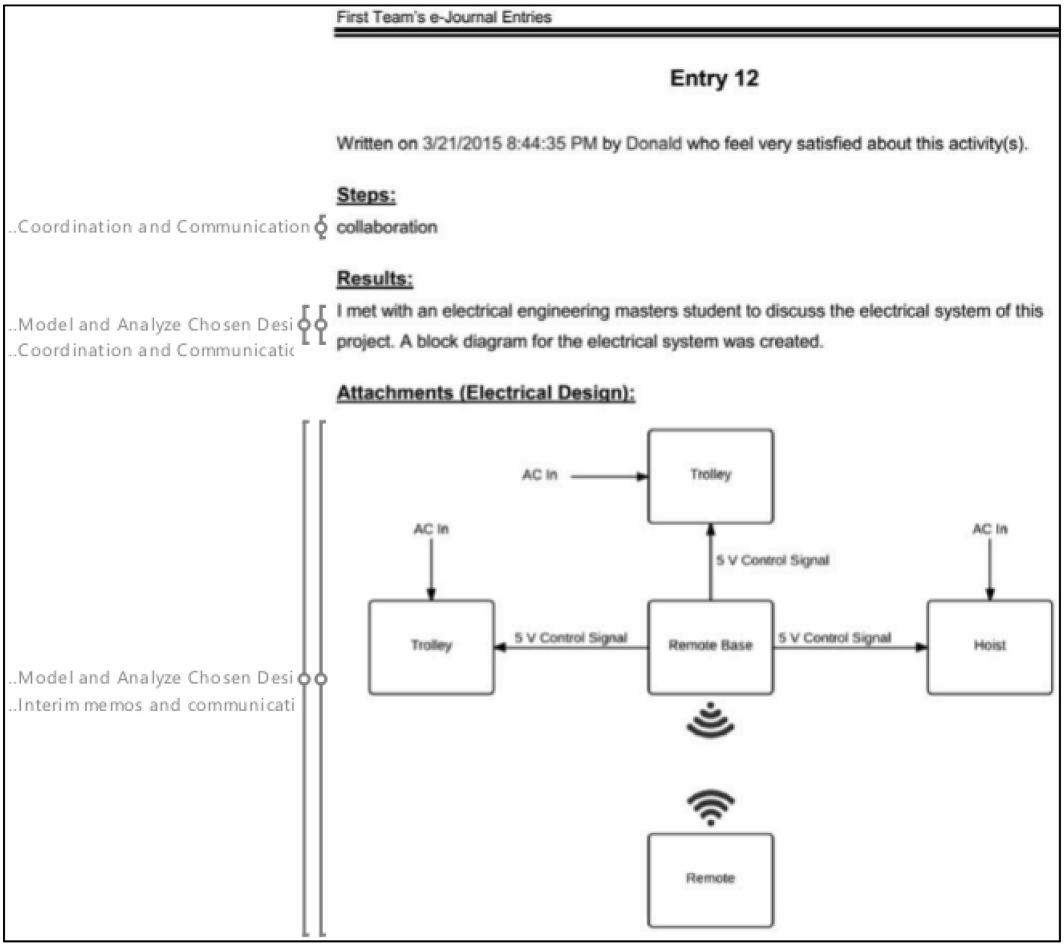


Fig. 1. A sample of Mechanical & Aerospace Engineering—Group 1's journal entry.

actions of a self-regulation process. We used Table 3 as a coding table to determine participants' task interpretation, planning, enacting, monitoring and fix up strategies during the design process. This analysis was conducted by one of the researchers over a 2- to 3-week period and produced 636 codes.

Following the segmentation and coding processes, a frequency analysis was performed to illuminate how contexts influence students' self-regulation. Frequency analyses were conducted for each discipline and group based on the number of design process, project management, design activities, and self-regulation codes.

Self-regulation is iterative in nature and evolves gradually [17]. Therefore, analyzing students' engagement only by frequency number is inadequate. Therefore, we conducted a chronological analysis by mapping the eJ entries based on the submitted date and time. Chronological map is one of the best methods to represent and understand the richness of a design process [75]. We called this chronological map of the design and cognitive process *flow*, or *process flow*, for short. Two types of process flow were developed. The first was the overall process flow, in which participants' engagement was presented in one map based on date and the activity types (e.g., problem definition or task interpretation). The second was the WBS item process flow, in which participants' engagement related to the same issue was presented in comparison to other activities in one map based on the date and activity types. The MAE groups' WBSs were acquired from their assignment submissions. The BE groups' WBS were developed based on their proposals and discussions with one of the BE experts. Table 4 presents each group's WBS.

6. Findings and discussion

The findings and discussion are organized into three subsections: the code frequency analysis, overall process flow analysis, and WBS process flow analysis. During the discussion, the analyses are integrated and compared with findings from other studies.

6.1 Code frequency analysis

On average, the BE and MAE groups had 901 and

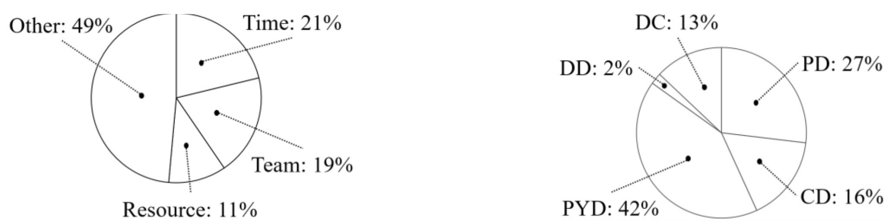
Table 4. Work breakdown structure

BE-G1	BE-G2
1. AMP construction	1. Drug binding
2. Fermentation	2. Drug release
3. Analyses	3. Device design
a. Purification analysis	4. Tissue testing
b. AMP yield analysis	
c. Activity analysis	
4. AMP yield optimization	
MAE-G1	**MAE-G2**
1. Body support and attachment	1. Power
a. Attachment to structure	a. Battery
2. Structure	b. On/Off switch
a. Main frame	2. Control
b. Subframe for/and movement Motors	a. Speed adjustment
	b. Disengage
3. Controls	3. Propulsion
a. User interface	a. Wheel
b. Electronics	b. Motor
4. Power system	4. Structure
a. Controls	a. Frame
b. Motors	b. Mounting bracket
	c. Suspension

258 codes in their journal entries, respectively. In total, 41% and 59% of the codes were related to project management and design process activities, respectively. The findings suggested that all participants reported engaging in managerial and design endeavors. Additionally, the participants reported immersion in project management activities almost as frequently as in design activities, which suggested that the participants gave relatively equal attention to their project management and design activities. This finding supported Dym and Little's argument that project management is an integral part of a design process [9], as shown in Fig. 2.

Based on Fig. 2 (a), our findings suggested that the participants engaged extensively in managing the other aspect of project management such as overseeing the design quality and risk (49%), followed by managing their time (21%), team (19%), and available resources (11%). This pattern was applicable to both the BE and MAE groups (see Table 5). Students seemed to pay the least attention to the management of resources-related issues. Other studies also reported similar finding, that students tended to put more self-regulation effort into managing the team compared to managing the resources [15, 76]. Since the term *resource* also referred to the project's budget and being able to complete the design under budget was one of the design project's criteria of success [6], the finding was problematic. We believe the limited design and project management experience influenced their minimal resource management engagement. Since lacking of self-regulation may have led to a failed problem-solving attempt [77], it was important to increase students' awareness and self-regulation skills related to this managerial aspect.

Based on Fig. 2 (b), our findings suggested that the participants engaged in various design activities, and most of their efforts were directed toward preliminary design activities. Most design codes were related to the preliminary design (42%), followed by the problem definition (27%), conceptual design (16%), design communication (13%), and detailed design (2%). Atman reported a similar finding, that students spend more time in modeling the solution [5], an activity related to the preliminary design phase. Interestingly, by analyzing the codes grouped by the discipline (see Fig. 3), we found that all problem definition codes belonged to the MAE groups, while all detailed design codes belonged to the BE groups. Since the BE groups were studied after they had finished the design proposal, not having problem definition-related codes was a justifiable outcome. On the other hand, not having any detailed design-related codes from the MAE groups was unexpected, especially since they were required to turn in the detailed drawings of their design at the end of the Capstone course. Consequently, we triangulated the unanticipated finding against the MAE groups' Canvas™ submissions, weekly report, and cloud storage data. The triangulation results suggested that the MAE groups were engaged in detailed design activities during the last few weeks of their Capstone course. Most of these activities were related to assign and fix the design details. Therefore, it was plausible that the MAE groups were engaged in various detailed



(a) Average total project management codes.

(b) Average total design process codes.

Fig. 2. Average total codes related to project management (left) and design process (right) (PD—Problem Definition; CD—Conceptual Design; PYD—Preliminary Design; DD—Detailed Design; and DC—Design Communication).

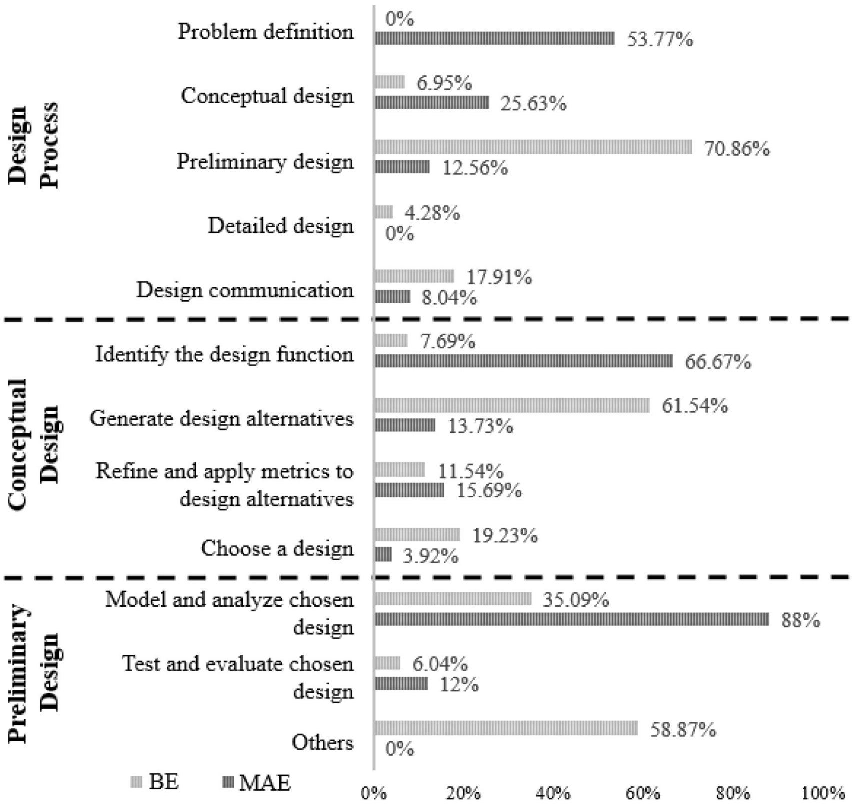


Fig. 3. Average percentage of design-related code frequencies.

design activities but failed to report them. Nevertheless, the data suggested that all groups were less engaged in detailed design activities. Interestingly, Sobek reported that detailed design engagement is not associated with the design quality [10].

Based on Fig. 3, the design process part, our findings suggested that the BE groups engaged in preliminary design extensively, while the MAE groups engaging primarily in problem definition. As presented in the figure, most of the BE participants' codes were related to the preliminary design phase (70.86%), followed by design communication (17.91%), conceptual design (6.95%), and detailed design (4.28%). Meanwhile, most of the MAE groups' codes were related to problem definition (53.77%), followed by conceptual design (25.63%), preliminary design (12.56%), and design communication (8.04%).

In their design journey map, the MAE groups reported that they spent a considerable amount of time identifying objectives and constraints and establishing metrics accurately under close guidance from the course instructor. Therefore, it was probable that the nature of course and discipline influenced the participants' problem definition engagement. Nevertheless, knowing that the MAE groups engaged extensively in problem definition was encouraging because studies reported that experts tend to spend more time in formulating the design problem [11], and that it positively associates with the design quality [10]. Further analysis of the groups' activities during the conceptual design phase (see Fig. 3) showed that all participants reported employing various conceptual design strategies. Most of the BE groups' codes were related to generating design alternatives (61.54%), followed by choosing a design (19.23%), refining and applying metrics to design alternatives (11.54%), and identifying design functions (7.69%). These reported activities were intriguing because based on their proposal, the BE groups had chosen their best design prior to the data collection. However, since the data suggests that the BE groups were immersed in generating design alternatives (61.54%), there must have been a condition that prompted them to return to the conceptual design phase. A follow-up analysis of this issue is discussed in the next subsection.

Based on Fig. 3, the conceptual design part, our findings suggested that the MAE groups engaged extensively in identifying the design function, and gave relatively equal attention to generating design alternatives and refining metrics to those alternatives. Their reported engagements in this phase were mostly related to identifying the design function (66.67%), followed by refining and applying metrics to design alternatives (15.69%), generating design alternatives (13.73%), and choosing a design (3.92%). Their code percentage of generating design alternatives was of concern because students who engage extensively and consider more design alternatives tend to produce a higher quality design [4]. Fortunately, based on the design proposal and artifacts, the MAE groups reported exploring existing design solutions, which according to Sobek [10], is beneficial to help designers producing a better quality design. During the preliminary design (see Fig. 3), most of the BE groups reported design activities were related to the other design activities (58.87%), which referred to any protocol-driven activities, such as when they were ''extracting plasmid from E. coli with B0015, Oh-Cath, LL-37, and Sphen2-B0015.'' According to the BE experts, these activities could not be categorized into one of Dym and Little's design strategies, but they were still related to the preliminary design phase. Further, they clarified such activities are common in the their field, which explains why there was no similar activity found in the MAE groups. Both BE experts then agreed to add another code (i.e., ''Others'') under the preliminary design phase.

Figure 3 also suggested that the BE groups put more attention and effort into modeling and analyzing the chosen design compared to testing and evaluating it. Interestingly, the MAE groups data also suggested a similar interpretation. In their study about the design process differences between first-year and senior students, Atman et al. also reported an analogous finding [4, 5].

As presented in Table 5, all participants engaged in various project management activities. As stated earlier in this subsection, the data suggested that both BE and MAE participants reported putting more effort and attention to other aspects of project management (e.g., scope management). By omitting the ''Others'' code category, our finding suggested that the BE and MAE groups immersed in various time and team management activities, respectively. As presented in the table, most of the BE groups' codes were related to time management (30.55%), followed by the management of team (14.80%) and resources (6.64%). Meanwhile the MAE groups' codes were mainly related to team management (23.73%), followed by the administration of resources (15.25%) and time (11.86%). It was plausible that the managerial priority difference between the BE and MAE groups was influenced by the nature of their design project. For example, biological engineers typically work with living organisms, especially for cloning in which they follow specific time-sensitive procedures [78–80], and each organism has unique characteristics. Consequently, it is difficult to predict a BE project's probability of success, cost, and completion time [79]. As for the MAE groups, most of the time each designer can work remotely as long as he or she has access to the internet [9]. Interconnectivity between all parts becomes essential, and can be attained by actively communicating the design solution within the team. Consequently, teamwork becomes prevalent for the MAE groups.

In terms of self-regulation, this research confirmed findings from other studies, such as during the design and project management, the participants reported engaging various self-regulatory activities [4, 5]. Further, as presented in Table 6, both the BE and MAE groups reported using more enacting and monitoring & fix-up strategies compared to task interpretation and planning strategies throughout their design and management activities.

Table 5. Average Percentage of the Project Management Code Frequencies

Project management	BE (%)	MAE (%)
Time	30.55	11.86
Team	14.80	**23.73**
Resources	6.64	15.25
Others	**48.01**	**49.15**

Table 6. Average Percentage of the Self-regulation Code Frequencies

Self-Regulation Feature	BE (%)	MAE (%)
Task interpretation strategies	13.79	18.06
Planning strategies	23.28	17.36
Enacting strategies	**38.22**	**30.21**
Monitoring and fix up strategies	**24.71**	**34.38**

6.2 *Overall process flow analysis*

We developed the design and cognitive process flow (e.g., Figs. 4 and 6) based on the eJ codes. The horizontal axis represents days, and each grid indicates a week. Thus, the first and last weeks are the leftmost and rightmost grids, respectively. The vertical axis represents the design process (e.g., Fig. 4) or strategic actions (e.g., Fig. 6). The dots represent the group members' reported activities on a particular day. Since the software does not make the overlapped dots thicker or bigger, it is possible that one point consists of more than one dot. Therefore, the analysis of process flows combines the number of design and self-regulation codes in each group (i.e., Tables 7 and 8) to overcome that disadvantage.

Design process flow. Figure 4 presents the BE-G1 and BE-G2 design process flows. The flows and number codes suggested that the BE groups engaged in various conceptual design, preliminary design, detailed design, design communication, and project management activities.

The three top codes of the BE groups were related

Table 7. Total Design Process Codes per Group

Design Phase	BE-G1	BE-G2	MAE-G1	MAE-G2
Problem definition (PD)	0	0	**24**	**188**
Conceptual design (CD)	5	45	19	83
Preliminary design (PYD)	**457**	**71**	17	31
Detailed design (DD)	9	22	0	0
Design communication (DC)	83	50	11	19
Project management (PM)	**817**	**235**	**28**	**87**

to PM, PYD, and DC throughout the data collection period. This finding suggested that both BE groups engaged extensively in various project management, preliminary design, and design communication throughout the design period. The findings related to design communication provided additional insight to Atman's studies [4, 5] in which it was found that students tend to withdraw from documenting their design process during 4 hours of the problem-solving enterprise. Our study found that given a longer design period, the BE students engaged in various design communication activities independently. This finding was encouraging because developing design representations contributes to producing a higher quality design [3]. Further, the BE groups' journal entries suggested that the engagements were influenced by their discipline best practices for continual analysis and error tracing. In their eJ, the BE-G1 group made it clear by writing:

> "To move forward, we need to locate the DNA sample, determine where we went wrong, and move forward from that step. Look through DNA samples and our lab notebook to see where things may have been mixed up."—BE-G1's entry 12

At that time, the BE-G1's design process was hindered because they failed to produce the required clones and then they decided to determine their mistake by tracing their design journal.

The BE-G1 and BE-G2 findings were different regarding the number and occurrences of codes related to conceptual and detailed design (Fig. 4 and Table 7). The number of codes suggested that the BE groups infrequently engaged in detailed design activities. There were five conceptual design codes for BE-G1, and they all occurred after the summer semester. Their journal entries revealed that they returned to the conceptual design phase due to problems related to constructing the AMP expression system and design analyses; a follow-up analysis of this issue is discussed in the next subsection. The BE-G2 had 45 codes related to the conceptual design phase, and their occurrences were outspread throughout the design process. Their journal entries revealed that the conceptual design activities were related to designing drug release mechanisms and devices; a follow-up analysis of this issue is discussed in the next subsection.

Both BE groups also showed a rise of instances near the 37th week (Fig. 4), which suggested an escalation in reported design activities near the end of the course. We discussed this pattern with the BE experts, and they confirmed that such behaviors are common among the undergraduate students, especially those who worked in their laboratory.

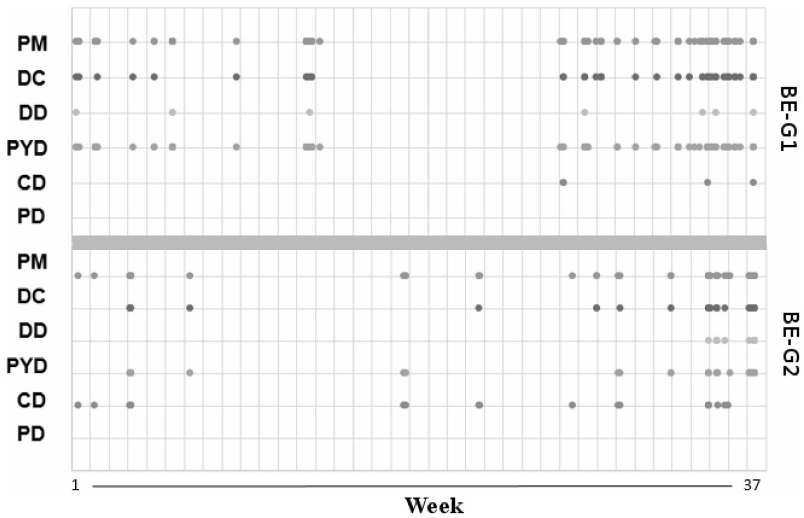


Fig. 4. Biological Engineering groups' design process flow (PD—Problem Definition; CD—Conceptual Design; PYD—Preliminary Design; DD—Detailed Design; DC—Design Communication; and PM—Project Management).

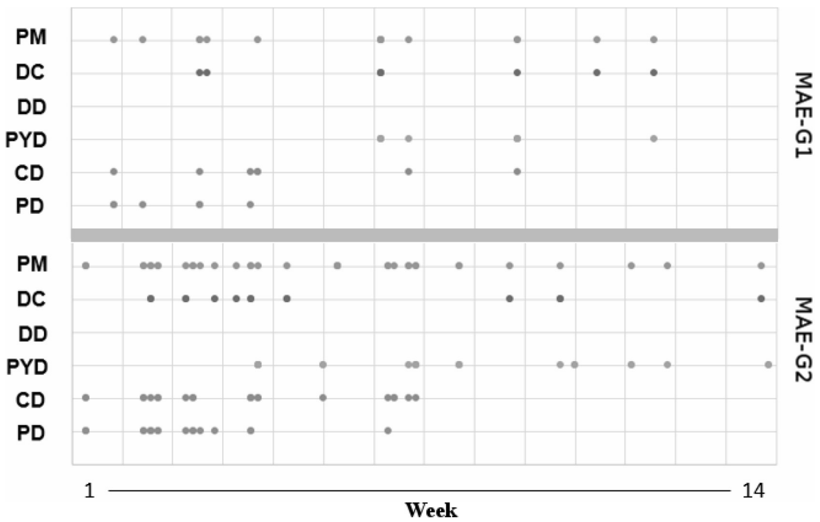


Fig. 5. Mechanical and Aerospace Engineering groups' design process flow (PD—Problem Definition; CD—Conceptual Design; PYD—Preliminary Design; DD—Detailed Design; DC—Design Communication; and PM – Project Management).

Figure 5 presents the MAE-G1 and MAE-G2 design process flows. The flows and number of codes suggested that the MAE groups engaged in various problem definition, conceptual design, preliminary design, design communication, and project management activities. The number of codes suggested that both groups had the same priorities, which were problem definition, project management, conceptual design, preliminary design, and design communication. Although both groups had more codes related to problem definition, these activities only occurred at the beginning of the design project. Additionally, the design process flow-topography suggested an incremental endeavor from the problem definition phase to conceptual, and then to preliminary design phases. The incremental pattern was unique to the MAE groups, and suggested distinct drivers in the design approach between BE and MAE groups. Based on the design proposal, artifacts, and course schedule, the BE groups' approach was driven by design task, while the MAE groups' was driven by design phase. It should be noted that although this study used the phase-based design process model, there are other types of design models that revolve around the design tasks [33]. Thus, it was plausible that varying design principles and practices in BE and MAE influenced their design approach.

The MAE groups also showed a similar pattern to the BE groups regarding design communication (Fig. 5). Although the number of design communication codes was the least compared to other codes, these activities occurred throughout the project duration. Based on the eJ entries, course syllabus, and the groups' presentations, the course required them to communicate their design to the instructor, experts, and clients. Thus, the course design influenced the MAE groups' behavior towards design communication activities. Also, it was plausible that the course instructor considered continuous design communication as an important part of a design process and tried to instill it in the students. Additionally, Fig. 5 suggests that the MAE groups engaged in various project management activities throughout the design period, and that project management was an integral part of the design process.

Self-regulation flow. Figure 6 presents the BE-G1 and BE-G2's SRL process flows. The flows and the number of codes suggested that the BE groups engaged in self-regulatory activities throughout the design process. Based on Table 8, our findings suggested that both groups gave more attention and employed more strategies related to their enactment strategies. Further, it suggested that the BE-G1 and BE-G2 employed the least task interpretation and

Table 8. Total Self-regulation Codes per Group

Self-Regulation Feature	BE-G1	BE-G2	MAE-G1	MAE-G2
Task interpretation (TI)	50	45	23	80
Planning strategies (PS)	134	27	23	76
Enacting strategies (ES)	**195**	**70**	**40**	134
Monitoring & fix up (MF)	126	46	26	**172**

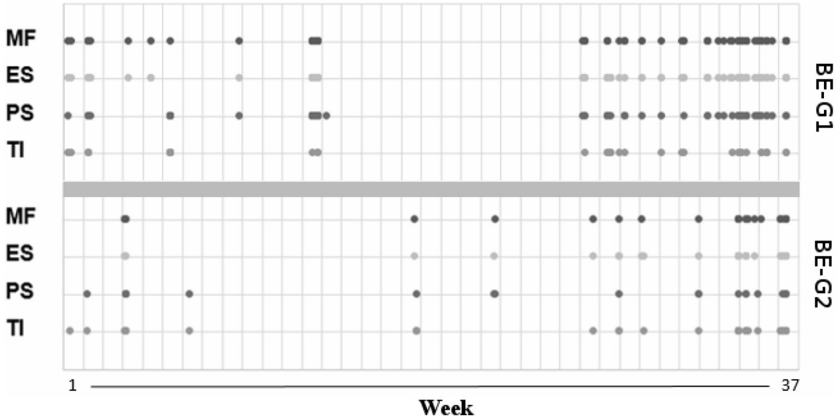


Fig. 6. Biological Engineering groups' self-regulation process flow (TI—Task Interpretation; PS—Planning Strategies; ES—Enacting Strategies; and MF—Monitoring and Fix Up).

planning strategies, respectively. Our data showed that the BE-G1 had more codes related to ES, PS, and MF compared to TI. It also showed that the BE-G2 had more codes related to ES, MF, and TI compared to PS.

Figure 7 presents the MAE-G1 and MAE-G2's SRL process flows. The flows and the number of codes suggested that the MAE groups engaged in various self-regulation activities throughout the design process. Based on Table 8, our findings suggested that both groups gave more attention to and employed more enactment strategies. Additionally, the findings suggested that each group employed various task interpretation and planning strategies at a similar level. Our data showed that the MAE-G1 had more codes related to ES compared to MF, TI, and PS. It also showed that the MAE-G2 had more codes related to MF and ES compared to TI and PS.

The MAE-G1's flow (see Fig. 7) suggested that their task interpretation activities only occurred at the beginning of the design project. This reported behavior is uncommon because identifying a task is the beginning of any self-regulation activities [59]. Based on the theory, we suspected that the MAE-G1 was unable to report their task interpretation activities in the journal.

It is worth noting that the BE-G2 and MAE-G1 had a fewer number of codes compared to the BE-G1 and MAE-G2, respectively. The finding suggested that either the BE-G2 and MAE-G1 were less engaged in the design process, or they were less involved in reporting their design activities. Unfortunately, it was not possible to confirm the correct interpretation based on the collected data.

6.3 WBS process flow analysis

Aside from the overall process flow, we also developed the WBS item design process and transition flows for each group. See Table 4 for a list of the WBS items in each group. In this paper, we only highlighted some of those process flows to answer the research question.

Dynamic Design Process. Figure 8 presents examples of the dynamic design process when working on some of the WBS items. In these examples, it was

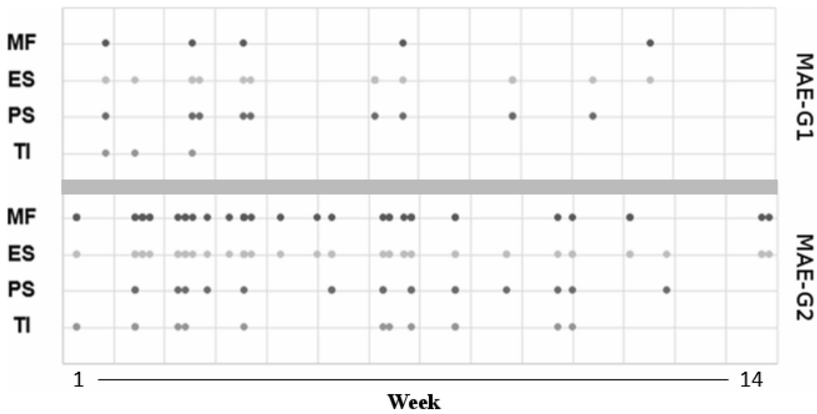
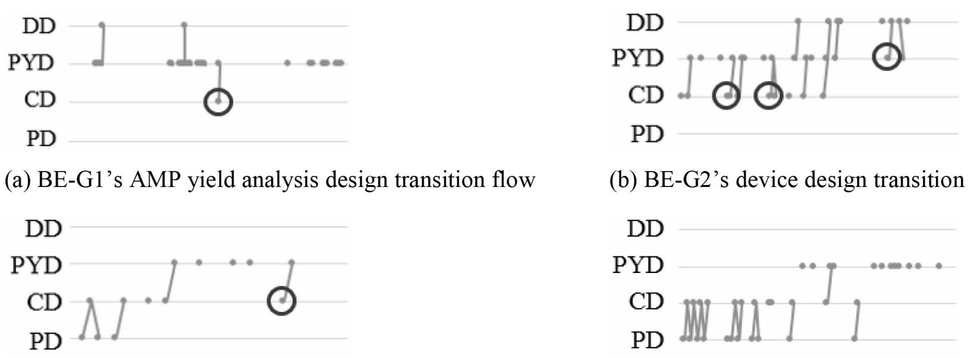


Fig. 7. Mechanical and Aerospace Engineering groups' self-regulation process flow (TI—Task Interpretation; PS—Planning Strategies; ES—Enacting Strategies; and MF—Monitoring and Fix Up)



(a) BE-G1's AMP yield analysis design transition flow

(b) BE-G2's device design transition flow

(c) MAE-G1's sub frame design transition flow

(d) MAE-G2's frame design transition flow

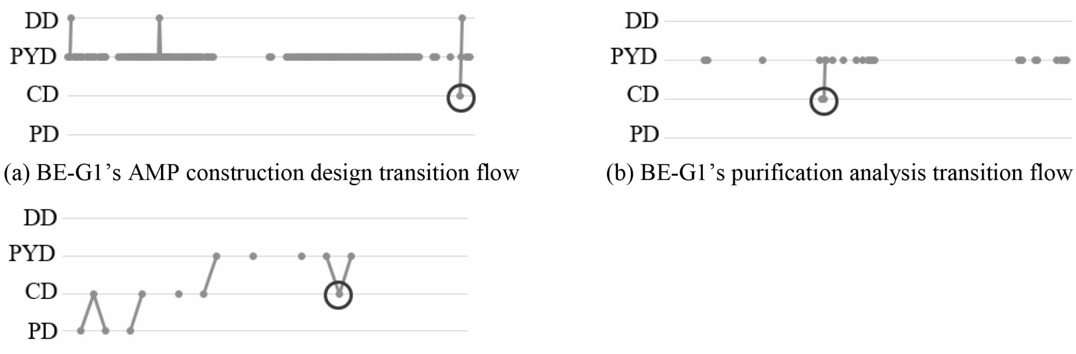
Fig. 8. Dynamic design transition flows (PD—Problem Definition; CD—Conceptual Design; PYD—Preliminary Design DD—Detailed Design).

apparent that the participants frequently moved back and forth between problem definition and conceptual design, conceptual and preliminary designs, and preliminary and detailed designs. The finding confirmed and provided additional insights to Atman's study [4], which found that students' design process is dynamic. Our findings suggested that the participants tended transition frequently between two adjacent design phases when working on a particular design issue. Considering how these patterns emerged in both the BE and MAE groups, it was plausible that the participants' design transitions were influenced by their progress (i.e., the nature of the design process). Studies suggested that the number of design transition influences the design quality [4, 5]. However, since a good project management approach aims to reduce the number of design iterations [30], it is important to train students to increase the quality of their design engagement while still keeping the number of design iterations low.

Return to previous design phase. As shown in Fig. 8, recurring transitions between the two neighboring design phases was a common pattern, and going back to the previous design phase was a natural part of the design process. Further analysis showed that it was uncommon for the participants to return to a phase after consistently (i.e., three instances) working in a particular phase. There were only eight instances in that category, which were presented and circled in Fig. 8 (a), (b), and (c), and Fig. 9. Five instances occurred because the participants were working on a different aspect of the solution. As an example, in the BE-G2's device design [see circled dots in Fig. 8 (b)], from left to right, they worked on the temperature display, heat transfer, and device housing (i.e., the container). The other three instances occurred because of various issues with the proposed design. For the BE-G1, the issues were related to unexpected mutation; they wrote, "had to switch out the GFP for CFP because of a mutation in the GFP stock" (BE-G1 entry 6.28). For the MAE-G1 [see circled dots in Fig. 9 (c)], they realized that the client's bathroom structure was unsuitable for the proposed solution. They wrote:

> "After visiting [client's] bathroom our design ideas changed. Discussed that the system will need to be a four post system, with 24v powered. Jason, Robert, and Kevin will create a 3D model of [the] bathroom and four post system."—MAE-G1 entry 10

When the group visited the client's bathroom, they

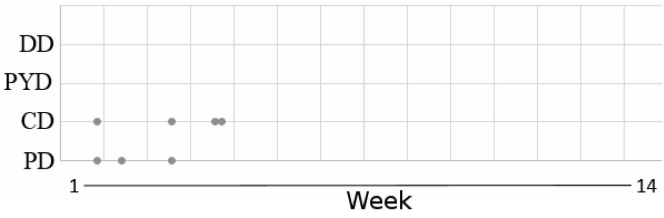


(a) BE-G1's AMP construction design transition flow

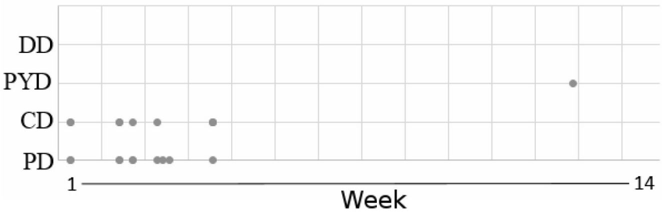
(b) BE-G1's purification analysis transition flow

(c) MAE-G1's main frame design transition flow

Fig. 9. Design transition flows (PD—Problem Definition; CD—Conceptual Design; PYD—Preliminary Design; DD—Detailed Design).



(a) MAE-G1's User Interface Design Process Flow (11 Codes)



(b) MAE-G2's On/Off Switch Design Process Flow (20 Codes)

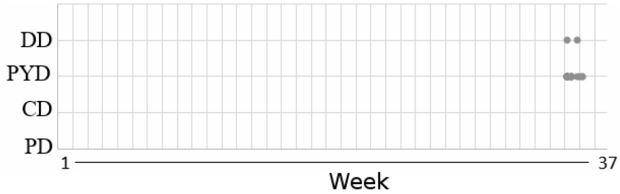
Fig. 10. Design tasks that are heavy at the beginning of the project duration (PD—Problem Definition; CD—Conceptual Design; PYD—Preliminary Design; DD—Detailed Design).

developed a working 3D model of the design solution. Their tenth entry, in the above-referenced entry quotation, was intriguing because it suggested that the group had never visited the client's bathroom during the problem definition phase. We confirmed this interpretation by trianggulating through their other journal entries, written interview responses, and design journey. We decided to explore the reason behind their behavior and found that the MAE-G1 assumed their client had a "typical residential bathroom." Interestingly, this group had never clearly defined and challenged their understanding of this term.

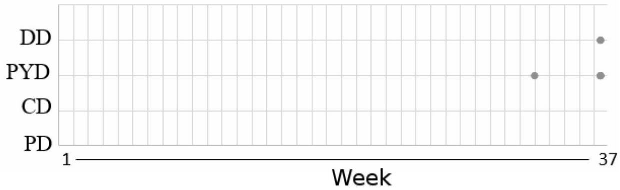
The MAE-G1 was not the only group who suffered due to their assumption. The BE-G1 also faced a similar problem. They wrote, "We found that every band cut with X looked weird and realized that we were using the restriction enzyme Xhol instead of Xbal" (BE-G1 entry 6.28.06). The BE experts commented that it was a common, novice bioengineer mistake. Atman reported that students occasionally develop assumptions during the design process, and the seniors tend to develop more assumptions compared to the freshmen students [4]. Thus, the students' assumptions influenced their self-regulation. Therefore, it is crucial for the students to understand the impact of developing incorrect assumptions.

Heavy at the beginning of the project. The WBS item design flow analysis revealed that some of the participants' design activities only took place at the beginning of the project. In BE-G2, the drug binding design was an example of that. In MAE-G1, there were electronics, user interface, and body and body support attachments. In MAE-G2, there was the on/off switch design. Fig. 10 presents some of those WBS items. To accurately understand the reason behind this pattern, we triangulated our interpretation with the participants' design proposal, design artifacts, design journey maps, and shared cloud storage. Based on the eJ entries and design proposal, we found that it was crucial for BE-G2 to design the drug-binding mechanism as soon as possible in that the remainder of their design tasks depended on it. They reported that they needed to find a way to denature the HSA, which was the chosen chemical used to bind the drug. The findings suggested that the BE-G2 understood the dependency among the WBS items and planned accordingly. On the other hand, some design activities were too simple and could be solved directly, including the MAE-G1's user interface and MAE-G2's on/off switch designs. Thus, the design complexity influenced the participants' self-regulation. Unfortunately, we also found that some participants failed to report their follow-up design activities, such as when the MAE-G2 worked on the body and body support attachments.

Heavy near the end of the project. The WBS item design flow analysis revealed that some of the BE groups' design activities only took place near the end of the project. For the BE-G1 and BE-G2, their design activities were related to AMP yield optimization and tissue testing, respectively. Fig. 11 presents both process flows. In both cases, the tasks were dependent on other WBS items, for instance, the AMP yield optimization task was dependent on the progress of all BE-G1's WBS items (i.e., AMP construction, fermentation, and analyses). Our finding suggested the BE groups understood the dependency among the WBS items and adjusted their plan accordingly. The finding is encouraging



(a) BE-G1's AMP Yield Optimization Process Flow (44 Codes)



(b) BE-G2's Tissue Testing Process Flow (18 Codes)

Fig. 11. Design tasks that are heavy near the end of the project duration (PD—Problem Definition; CD—Conceptual Design; PYD—Preliminary Design; DD—Detailed Design).

because it is natural to have dependencies in some of the design tasks [30]. Further, the finding showed how the nature of the design process influenced the participants' design approach.

7. Discussion

We recruited four groups of senior engineering students to learn about students' self-regulation during the engineering design process in a Capstone course and the influence of contexts on their self-regulation. Our analysis suggested that the BE and MAE groups employed various SRL strategies at varying levels of intensity during their design and project management activities throughout the project duration. Our research confirmed and refined findings from various studies that reported the discipline, prior problem-solving experiences, current problem-solving progress, and problem decomposition, dependencies, and complexity that influences students problem-solving endeavor [5, 7, 8, 81–84]. We found three prominent contexts that influenced the participants' self-regulation during the design process: the nature of the design process, the nature of engineering projects in the discipline (i.e., biological, and mechanical, and aerospace engineering), and designers' experience.

We discovered that the nature of the design process influenced the BE and MAE groups to employ similar strategies throughout the design process. There were six behaviors that were primarily influenced by the nature of the design process. First, all participants devoted similar attention and effort to their design and management activities. The finding also suggested that managing a design project was as difficult as designing the most appropriate solution it. Second, they engaged extensively in design communication throughout the design period. The finding also provided additional insight to Atman's studies [4, 5] in which it was found that students tend to withdraw from documenting their design process during the 4 hours of the problem-solving enterprise. Our study found that given a longer design period, the students engaged in various design communication and documentation activities independently. Third, the participants adjusted their design approach based on their progress. Fourth, all participants developed assumptions throughout the design process. The finding also confirmed Atman's report on the same issue [4]. Fifth, the participants had frequent design transition between two adjacent design phase (e.g., between problem definition and conceptual design phases). The finding provided additional insights to Atman's study [4], who reported that students' design process is dynamic. Sixth, all participants employed various self-regulation strategies during the design process. The findings suggested that students displayed all six behaviors during the design process regardless of their specific discipline. It may be concluded that exposing students to the engineering design process helps them to better understand the nature of the discipline.

We discovered that the nature of engineering projects in the discipline influenced the participants' self-regulation. For example, the BE participants put more emphasis on time management, while the MAE participants emphasized team management. Additionally, the participants' process flow-topography suggested that the BE groups' design process was driven by the design tasks, while that of the MAE groups' was driven by the design phases. We found that as a discipline, the BE drew their knowledge from mathematics, physics, chemistry, and life science, and the MAE drew theirs from math and physics [78]. Consequently each field affects the discipline's principles and practices [78, 85]. Some studies reported that knowing the discipline is a crucial aspect of interpreting a task accurately [86] and that employing domain-specific strategies during a problem-solving endeavor is more efficient compared to using general strategies [17, 87]. Thus, eliciting disciplines-related objectives, constraints, problem-solving approach, and other issues during a class instruction would beneficial for the students. Unfortunately, the body of research that can help instructors and students understand discipline as a context is lacking [23]. Further, this finding also informed course instructors of the complexity of working in a multidisciplinary engineering project, in which students must be able to not only self-regulate themselves to the nature of their discipline, but also to the nature of other disciplines involved in the project. Conducting follow-up investigations on co- and shared-regulation is recommended to better understand students' self-regulation in a multidisciplinary engineering project.

We discovered that participants' experience influenced their self-regulation. There were four types of behaviors that were primarily influenced by the participants' experience. First, all participants engaged extensively in preliminary design, especially in modeling and analyzing the chosen design. This finding confirmed reports from other studies [4, 5]. Second, they were less engaged in detailed design activities. Third, all participants were less engaged in managing their resources. Fourth, they had an increase of activities near the end of the semester, suggesting a probable lack of self-regulation skills in time management. Fourth, both groups failed to check their assumption which then hindered their design process, suggesting a lack of self-regulation skills, especially self-monitoring.

8. Limitation and future work

There were a number of limitations of the current study. First, it focused only on the participants from biological, mechanical, and aerospace engineering disciplines. Further study is suggested to include broader engineering disciplines, such as computer science and electrical engineering. Second, the study selected only two cases from each discipline. Further study might include more cases to capture a wider variation of students' self-regulation activities and how contexts influence those activities. Third, the study did not assess the BE groups' self-regulation during the problem definition phase. Although replication studies are undervalued in the current engineering education community, such studies are "essential to moving toward a more reliable and trustworthy understanding of educational environments" (p.313) [88]. Thus, we encourage fellow researchers to replicate our study and improve its applicability by addressing our limitations.

9. Conclusion and implication

The approach of the participants to a design problem was influenced primarily by three contexts: the nature of the design process, the nature of the design project, and their experience. Being aware of the nature of the design process helped the participants to be cognizant of how all of the design aspects and phases (e.g., problem definition and project management) were equally important. Being aware of the nature of the design project helped the participants to select and apply the most effective general and discipline-specific strategies to solve the design tasks. Thus, the students were likely to achieve a heightened awareness of the nature of the design process and project in order to ultimately become better engineers. In this study, the participants' lack of design experience contributed negatively to their design process. For example, it was observed that the participants sometimes failed to check their assumptions and, thus, their progress was hindered. Although making assumptions is a common strategy in engineering design, it would be beneficial for the course instructor to design a case study or an activity that would illustrate the disadvantage of having unchecked or unconfirmed assumptions and would train the students in the art of self-monitoring.

Acknowledgements—This material is based upon work supported by the National Science Foundation (NSF), U.S.A. under Grant No. 1148806. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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