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# Self-Regulation Strategies in an Engineering Design Project

Oenardi Lawanto[1], Andreas Febrian[1], Deborah Butler[2] & Mani Mina[3]

[1] Department of Engineering Education, Utah State University, USA

[2] Department of Educational and Counselling Psychology and Special Education, Faculty of Education, University of British of Columbia, Canada

[3] Department of Electrical and Computer Engineering, Iowa State University, USA

Correspondence: Oenardi Lawanto, Department of Engineering Education, Utah State University, 4160 Old Main Hill, Logan, UT 84322-4160, USA. Tel: 1-435-797-8699. E-mail: olawanto@usu.edu

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**Abstract**

Models of self-regulation describe how individuals engage deliberately and reflectively in goal-directed action in order to achieve valued goals. Studies have found that the consistent use of self-regulation in an academic setting is highly correlated with student achievement. Self-regulation plays a critical role in problem-solving, particularly when unraveling ill-structured problems as is required in engineering design. The primary research question: How did engineering students perceive their self-regulation activities while engaged in a design project? A total of 307 students from three higher education institutions working on their capstone engineering design projects participated in the study. The study evaluated students' self-regulation in relation to both design and project management skills. We used a self-regulation in engineering design questionnaire (EDMQ) to assess students' approaches to self-regulation. Quantitative data were analyzed in two parts using descriptive and inferential statistics. Findings suggested that: (1) Students focused more consistently on task interpretation than other self-regulatory strategies, particularly during design; (2) Students lacked awareness of the essential need to develop a method to assess the design deliverables; (3) Self-regulation gaps were found during early design phases, but as the design process progressed, a more balanced approach to self-regulation was apparent. Given the importance of task interpretation to successful performance, students attended to identifying tasks during both the design process and project management. However, they did not report engaging in planning, implementing, and monitoring and fix-up strategies as consistently, even when those processes were relevant and called for. Implications are drawn for research, theory, and practice.

**Keywords:** engineering design, self-regulation, project management

## 1. Introduction

Design is considered to be a core task that helps engineering students develop problem-solving skills, critical thinking (Jonassen, 2004; Jonassen, 2000, 2010), and creativity (Christiaans, 1992; Daly, Mosyjowski, & Seifert, 2014; Dorst & Cross, 2001; Kozbelt, Dexter, Dolese, & Seidel, 2012). An integral part of undergraduate engineering education is often a multi-semester senior course sequence in "capstone" design. These courses are typically designed to promote learning transfer; it provides a professional learning experience that represents the design process and project management similar to what can be expected in the engineering workplace. The capstone design course provides engineering students with the opportunity to apply the knowledge and skills learned during their undergraduate program to solve design problems representative of those encountered in business and industry (Engineering Accreditation Commission, 2013; Farr, Lee, Metro, & Sutton, 2001), and to start learning how to learn through design experiences. Through first-hand knowledge of how the engineering design process works in a simulated business and industry environment, students are expected to become prepared for engineering practice. This kind of course also serves as a measure of their readiness for work at the professional level.

However, a recently completed STEM Talent Expansion Program (STEP) project (Froyd, Fowler, Layne, & Simpson, n.d.), which implemented a number of projects in first-year engineering courses at Texas A&M University (TAMU), found that students lacked the abilities needed to manage learning and problem-solving in those courses. Schoenfeld (1983) argued that unsuccessful problem-solving may result from difficulties in learners' self-assessments and strategic decisions. These self-assessments and strategic decision-making skills are at the core of one's self-regulation processes during design activities or while solving any problems or tasks. Indeed, self-regulation has been found to play an important role in solving problems, particularly ill-defined ones, as is required in design tasks (Atman, Cardella, Turns, & Adams, 2005; Atman, Chimka, Bursic, & Nachtmann, 1999; Dym & Little, 2008; Lawanto, Cromwell, & Febrian, 2016; Ward, 2013).

This study focused on students' approaches to self-regulation (SR) in the context of capstone design activities. Self-regulation refers to how students deliberately and reflectively control their thoughts, feelings, and actions in order to achieve valued goals (Zimmerman, 2008). While much research has focused on how students self-regulate their learning in classroom settings (e.g., while studying for a test), Butler, Schnellert, and Perry (2017) explain that the term *SR* can be used to describe an individual's goal-directed, strategic engagement in any sort of activity (including professional practice). In the context of capstone experiences, engineering students are being asked to self-regulate their engagement in design as a problem-solving activity (i.e., to achieve design requirements). At the same time, they are expected to start advancing their learning through engagement in authentic design activities (i.e., from learning *about* design to learning *through* design activity), as they will need to do throughout their careers as practicing professionals. When engineering students engage in authentic design activities that require SR, they have opportunities to develop metacognitive knowledge and skill that will support future problem-solving performance.

It is expected that the findings of the study will broaden the limited knowledge about how students take up opportunities for SR when engaged in capstone design experiences, which will inform engineering educators and developers of instructional engineering curricula. Having a better understanding of student SR in capstone activities will help engineering educators to design and implement teaching interventions that promote student metacognitive awareness, and as a result, encourage students' development of more intentional, reflective, and strategic engagement in learning within and through design tasks.

## 2. Relevant Literature Review

### *2.1 Self-Regulation Strategies*

As described above, SR refers to students' intentional, deliberate control of their thoughts, feelings, and actions in order to achieve valued goals (Butler et al., 2017; Zimmerman, 2008). Strategic action, which is at the heart of models of SR, includes iterative and recursive cycles of interpreting requirements, planning (e.g., resources, time, strategies), implementing cognitive processes, monitoring progress, evaluating progress against internal and external standards, and continually refining approaches so as better to achieve goals (Butler, 1995; Butler & Cartier, 2005; Flavell, 1979). Numerous studies have found that enhancement of SR abilities strengthens learning skills (Adelson & Soloway, 1985; Butler, 1995; Crippen, Schraw, & Brooks, 2005; Georghiades, 2000; Lawanto, 2010; Lawanto & Johnson, 2009; Pintrich, 2002; Veenman, Elshout, & Meijer, 1997; Wolters, 1998) and improves academic success (Andrade & Valtcheva, 2009; Boekaerts, 1997; Bransford, Brown, & Cocking, 1999; Downing, Kwong, Chan, Lam, & Downing, 2009; Ferla, Valcke, & Schuyten, 2009). For example, Zimmerman and Pons (1986) found that consistency in employing the SR processes is highly correlated with student achievement.

According to Zimmerman, Heart, & Mellins (1989), self-regulated learners are "metacognitively, motivationally, and behaviorally active participants in their own learning process" (p. 329); therefore, self-regulated learners are skilled in goal-setting, self-monitoring, self-instruction, and self-reinforcement (Schraw, Crippen, & Hartley, 2006). As a metacognitive control process, SR is closely tied to metacognition, which is loosely defined as knowledge and processes associated with thinking about thinking (Butler, 2015). Metacognitive skills are essential in all learning contexts because they "help students become active participants" (Paris & Winograd, 1990, p.18), especially when solving problems that involve ambiguous goal specifications, lack a clearly predetermined path leading to a satisfactory solution, and require integration of multiple knowledge domains such as design (Reitman, 1965; Simon, 1973).

The dynamic and iterative interplay between metacognitive and cognitive activities is clearly described by Butler and Cartier (Butler & Cartier, 2004a, 2005, 2018; Butler, Schnellert, & MacNeil, 2015; Cartier & Butler, 2004, 2016) in their SR model, which characterizes SR as a complex, dynamic, and situated learning process (Butler et al., 2017). According to Butler and Cartier, the quality of students' SR is influenced by multiple layers of context. Contextual influences are established by how activities are situated in a given country, state/province, school, or classroom, and are linked to particular teachers, instructional approaches, curricula, and learning activities. In engineering education, contexts include learning expectations in design courses, the nature of particular design tasks, and the expectations of the instructor. For example, a capstone design activities as presented in a given multi-semester course may create opportunities for SR, and the qualities of supports provided in that context may usefully guide learners to identify the most appropriate strategies to be used in that situation. Studies reported that students adjust their problem-solving approaches based on the contexts surrounding the task (Lawanto & Febrian, 2018; McNeill, Douglas, Koro-Ljungberg, Therriault, & Krause, 2016). Thus, recognizing the ways in which multiple interlocking contexts shape and constrain the quality of student engagement in learning is essential for understanding SR.

Butler and Cartier's model also describes the interplay between a learner's metacognitive and cognitive activity as activities unfold. From a metacognitive perspective, they describe SR as relying on both students' knowledge and beliefs about themselves and tasks (i.e., metacognitive knowledge), as well as their deliberate control over their engagement in activities (i.e., metacognitive control) (Butler, 2015; Flavell, 1979). As students manage their activities in tasks, they engage in iterative cycles of strategic activity, including actively interpreting requirements (i.e., interpreting tasks or TI), developing a plan of action (i.e., planning or PS), acting on developed plan (i.e., enacting or ES), monitoring progress and results (i.e., monitoring or MF), and adjusting approaches if necessary (i.e., adjusting or MF). From a cognitive perspective, their model explains how students' cognitive processes are situated within cycles of strategic activity (i.e., shaped by their choices of effective learning approaches in a given situation).

Key in the Butler and Cartier model is the idea that students' approaches to an activity depend heavily on how they perceive and interpret conditions in the environment. For example, students' perceptions of task requirements influence choices they make about appropriate plans and strategies (Butler & Cartier, 2004c); their reaction to feedback depends on how they interpret feedback messages (Butler & Winne, 1995). Research also documents how students' approaches to SR are heavily connected with their emotions as generated within environments (Boekaerts, 2011) and the motivational beliefs they bring to (and generate during) activities (Zimmerman, 2011).

Understanding SR as involving a combination of metacognitive and cognitive processes as situated within contexts provides a powerful framework for studying both how students engage in capstone design activities, which are typically complex, ill-structured, and involve multiple phases, and for imagining how to shape environments to effectively foster learning through design activity. Butler and Cartier's model implies that to be successful in navigating design tasks, students need to engage deliberately and thoughtfully in recursive cycles of strategic action, including on-going task interpretation, planning, enacting, monitoring, and adjusting activities. As part of the strategic action, they need to deliberately choose and then enact effective cognitive processes for accomplishing tasks, which in the context of engineering design, include defining a design problem, identifying constraints, generating design alternatives, and modeling a design solution.

### *2.2 Cognitive Strategies in Engineering Design*

Working on an open-ended task such as designing an engineering artifact is expected to be a rich learning experience for students. However, without support, engaging effectively in such open-ended, ill-structured tasks can be complex and challenging. Design may have numerous solution paths and be bound by constraints, which are not always presented with the problem. In order to be successful on such a task, students must know how to set reasonable goals for themselves and adopt intrinsic standards for success so that they will be able to solve problems strategically. Many studies (Atman et al., 2007, 2005, 1999; Cardella, Atman, & Adams, 2006; Cross, 2000; Dym & Little, 2008; Jonassen, Strobel, & Lee, 2006; Kim & Kim, 2015; Lawanto & Santoso, 2014; Lee & Johnson-Laird, 2013; Sobek & Jain, 2007) have found that students' cognitive and metacognitive skills (i.e., monitoring and controlling one's cognitive processes) play an essential role in problem-solving processes, particularly in solving ill-structured problems such as design. In other words, engineering design tasks require effective forms of SR.

Solving an engineering design problem should also be a structured and staged process. Modeling the design process as a phase-based model is more practical and suitable for students (Wynn & Clarkson, 2005). The ways in which students use cognitive strategies, observe what transpires, and search for alternative solutions are rich examples of how metacognition and cognition intertwine through design activities. There are many models that describe the engineering design processes in phase-based manner (Christiaans, 1992; Dieter & Schmidt, 2009; Dym & Little, 2008; Eggert, 2010; Ertas & Jones, 1993; Jones, 1988; Kusiak, 1999; Mawson, 2003), but despite their distinct differences, all phase-based models share similar design steps (i.e., 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 chosen design, and communicating the design).

For this study, we drew on Dym and Little's (2009) prescriptive model to identify students' cognitive strategies and metacognitive activities during five design phases. This design model was selected for two reasons. First, it captures the similarities of existing phase-based models' design steps in its five main phases (i.e., problem definition, conceptual design, preliminary design, detailed design, and design communication) with specific design strategies in each phase. Second, it acknowledges project management as an integral part of the design process. Table 1 shows a summary of cognitive strategies identified in the Dym and Little model for each of the design phases.

Dym and Little's design phases are considered as high-level, overall views of the design process. They involve a sequence of cognitive and metacognitive actions or strategies that relate to the current state of the design process. For example, during the problem definition phase, students are expected to understand the design problem. Defining the problem requires four strategies (clarifying objectives, establishing metrics for the objective, identifying constraints, and revising the client's problem statement). In one study post-secondary students identified the problem definition phase of the design process, which requires analyzing the problem from different perspectives, to be the most important engineering design activity (Atman, Kilgore, & McKenna, 2008). This finding aligns with Butler and Cartier's emphasis on the importance of "task interpretation" in effective forms of SR (Butler & Cartier, 2004b; Butler & Winne, 1995), since students' decisions about all further activities hinge on how they interpret task requirements. Note that cycles of strategic action are important in all design phases regardless of their design focus. This is because students must continually work towards relevant goals as established in that design phase (e.g., keeping in mind the goals of the detailed design phase), and to plan, enact, monitor, and adjust approaches as needed (e.g., to accomplish goals associated with detailed design).

Table 1. A five-stage prescriptive model of the design process with design strategies based on Dym and Little (2009)

| Design Stage | Design Strategies |
|---|---|
| Problem Definition | Co–Clarify objectives<br>Emo–Establish metrics for objectives<br>Ic–Identify constraints<br>Rp–Revise client's problem statement |
| Conceptual Design | Ef–Establish functions<br>Er–Establish requirements<br>Emf–Establish means for functions<br>Ga–Generate design alternatives<br>Ram–Refine and apply metrics to design alternatives<br>Cd–Choose a design |
| Preliminary Design | Ma–Model and analyze chosen design<br>Te–Test and evaluate chosen design |
| Detailed Design | Rod–Refine and optimize chosen design<br>Afd–Assign and fix design details |
| Design Communication | Dfd–Document final design |

*2.3 Project Management in Engineering Design*

Many scholars address the prevalent nature of hands-on design projects for engineering students in their senior year, particularly during senior capstone design courses (Dutson, Todd, Magleby, & Sorensen, 1997; Gordon, 2008). As part of these projects, students have to engage effectively, not only in design processes as defined by Dym and Little, but also in project management. Kerzner (2013) defined project management as an approach for finding internal solutions to resource-control issues and requires "methods of restructuring management and adapting special management techniques, with the purpose of obtaining better control and use of existing resources" (p. 2). Project management in this study was defined as comprising three elements: team management, resources management, and time management. The separate components of project management each involve dynamic decision making and require a high level of SR as students work to overcome the various challenges associated with each aspect.

In completing their design projects, engineering students typically work with their fellow students (Ward, 2013). Team management typically involves dynamic coordination of 3-6 persons, their personalities, and various agendas. Team management is particularly important in design projects. Working in a team is not always easy and often brings more complexity to the design project on which they are working (Curşeu & Schruijer, 2010; Oliveira & Sadler, 2008). Working in a team is not just about working together with peers and sharing the same space and tasks; it also involves balancing power and responsibility as they seek to control the path their team takes to meet its mission. Loughry, Ohland, and DeWayne-Moore (2007) in their peer-assessment instrument describes complex interplay among team members, including assessing contribution, interaction, monitoring progress, quality control, and relevant knowledge. In the context of design capstone courses, students are both responsible for negotiating the progress through design activities and for co-regulating their learning together (Hadwin, Jarvela, & Miller, 2011; Volet, Vauras, & Salonen, 2009).

Numerous studies have suggested that group learning offers a basis for social comparison and social learning (Solomon, Croft, & Lawson, 2010), and that teamwork quality and team diversity impact the effectiveness and quality of task completion (Curşeu, Schruijer, & Boroş, 2007; Menekse, Higashi, Schunn, & Baehr, 2017; Stevenson & Starkweather, 2010). For example, one study reported that students' approaches to understanding and solving a design task are influenced by their peers (Rivera-Reyes, Lawanto, & Pate, 2016). Passow & Passow's (2017) systematic literature review concluded that academia considered teamwork as one of the most important competencies that any engineering undergraduate students should have. In the context of engineering senior design projects, the project mission is accomplished as students manage the demands of tasks and assignments from clients (someone who inspires or supports the design project), the instructor, and each other. In this study, we did not focus on students' co-regulation of learning through engineering design. Instead, as part of project management, our attention focused on how each member of a team self-regulated (i.e., understood, planned, enacted, monitored, and adjusted) their activities to give a fair contribution to the team.

In this study, we defined resource management as including tracking and using facilities, tools, materials, supplies, and funding. Challenges can range from undersized budgets to competing for crowded lab space and tools. We singled out time management as a unique component of project management because it may represent one of the most ill-defined parameters within a capstone engineering design project. There may be due dates for course required milestones, but students are often required to set a pace based on their own level of commitment to their team and their project. In this study, time management was considered on an individual basis, as students' prioritized work on their particular project tasks and coordinated with teammates to meet pre-determined deadlines for delivering portions of the project.

### *2.4 Students' Self-Regulation in Engineering Design*

Prior studies have identified how engaging in authentic design activities shapes students' approaches to SR in design. For example, Moore, Miller, Lesh, Stohlmann, and Kim (2013) found that students' initial SR was influenced by their intuitive interpretation of the design problem. But then their approaches to and understanding about the task shifted as they continuously and iteratively interacted with the problem, which usually involved developing and transitioning between multiple problem-representations. Others have also found that students change their task understanding as they advance in their engineering program (Carberry & McKenna, 2014) and their problem-solving endeavors (Febrian, 2018; Rivera-Reyes, 2015; Rivera-Reyes, Lawanto, & Pate, 2017). Litchfield, Javernick-Will, and Maul (2016) argue that students' exposure to realistic, contextualized, and complex design tasks improves the quality of their design and SR.

Prior research has also identified strengths and limitations in engineering students' engagement in SR during design activities. For example, in research conducted at the post-secondary level, students considered the understanding of the problem to be the most important engineering design activity (Atman et al., 2008). After clearly understanding the problem, they may be ready to propose a solution, analyze it, and decide whether to use it or find alternatives. Seniors found identifying constraints and iterating design more important than did first-year students (Atman et al., 2008; Lawanto, 2011; Lawanto et al., 2013). In our prior study of engineering design at in grades 9-12, we found that students invested more effort in task interpretation than in developing proper plans, selecting design strategies to implement the plans, and monitoring performance while defining design problems and developing conceptual design solutions (references). Gaps between students' interpretation of task demands and selecting design strategies for task completion and monitoring/adjusting were also present. We were particularly interested in understanding how students perceived their engagement in design activities, both from the design and project management perspectives.

## 3. Research Purpose and Question

This study was conducted to describe student SR during engineering design tasks in relation to both design and project management activities. The research question guided this study: "how did participating engineering students perceive their SR activities while engaged in a design project?"

## 4. Research Participants and Design Projects

The participation of the students in the study was voluntary. Two hundred and forty eight electrical engineering students volunteered from Iowa State Universty, during fall 2014 and spring 2015 semesters. For every five completed surveys, one $25 gift card was given to one of the participants who selected through a lucky draw. Two hundred and twenty-three (92%) of the research participants were male, and twenty (8%) were female. They had a GPA between 2.00 and 4.00 on a 4-point scale; sixty-five percent of the students had a GPA of 3.00 or above. The ethnicity of the participants was African American (3%), Asian-Pacific Islander (13%), Caucasian (74%), Hispanic (1%), and other (9%).

The students worked on their capstone design projects in teams of 3 to 6 persons. Students signed up for the projects and could suggest their preferred team. Before signing up, class instructors made sure that students chose the type of project that was aligned with their interests. Senior design faculty occasionally added one or two additional members to students' selected teams.

The context of the design in which the research participants engaged were senior design capstone project courses across three different institutions. For these courses, projects were proposed by faculty and industrial partners. Each was one of the core courses that participating engineering students needed to take before completing his or her undergraduate engineering programs. Based on numerous reported studies (Atman et al., 2005, 2007; Hotaling, Fasse, Bost, Hermann, & Forest, 2012; Litchfield et al., 2016; Lutz & Paretti, 2017), we expected the participants were experienced in employing various design and managerial strategies.

Each project had a client and each team was assigned a faculty advisor. Students worked with their client as well as their faculty advisor throughout the project. The design projects were varied in terms of the topics, expected deliverables, specialized resources, and anticipated costs. For example, one group collaborated with Riemann Gardens Entomology to design, develop, and release an app for the Google Play store. The app had the potential to significantly and positively alter the course of global conservation research. Another group worked on a system to establish a wireless network connection between two remote locations without the use of wireless Access Points or cell phone towers. The system was designed to use Android devices as wireless repeaters to establish a chain starting at some locations.

## 5. Data Collection and Analysis

Students' SR in the design process and project management was analyzed using the Engineering Design Metacognitive Questionnaires (EDMQ) survey instrument. The survey was grounded in Butler and Cartier's model of SR which describes the interplay between motivation, cognition, and metacognition in a design activity. In previous research, the EDMQ was developed by cross-referencing strategic action in Butler and Cartier's model (i.e., task interpretation, planning strategies, cognitive strategies, and monitoring/fixed-up) with both Dym and Little's design phases (i.e., problem definition, conceptual design, preliminary design, detailed design, and design communication) and project management components (i.e., teamwork, time, and resource management). The EDMQ was utilized in this study to ascertain students' perspectives on their engagement in SR during the design process and project management. In other words, we used the EDMQ, not as an indicator of students' activity in the project per se, but as an indication of how students perceived their engagement in design activities, as the activity unfolded. EDMQ allows us to have a glimpse of students' cognitive activities in a way that a direct observation cannot provide.

Content, construct, and face validities of the EDMQ instrument (94 items total) were established in previous research. The Cronbach's alpha scores in this study (for task interpretation – 18 items, planning strategies – 19 items, design enacting strategies – 27 items, and monitoring & fix-up strategies – 30 items), which are ranged between 0.83 - 0.97.

The survey instrument was divided into three subsections to capture students' perceptions of their engagement in self-regulated learning at the early, middle, and final stages of the design task, respectively. In order to increase the validity of students' reported perceptions, we aligned administration of the EDMQ sections with students' engagement with different phases in the design project. Specifically, during the data collection, students were asked to complete these three subsections of the survey instrument. The first subsection of EDMQ captured students' strategies during the problem definition and conceptual design stages, and was administered near the end of the conceptual design stage in the course. The second subsection captured students' strategies during the preliminary and detailed design stages, and was administered near the end of the detailed design stage. The third subsection captured students' strategies during the design communication stage and project management tasks, and was administered before the participants presented their final design. Response options for the items recorded students' reports of strategy use during the design task on a scale from 1 to 4 (i.e., 1 = almost never, 2 = sometimes, 3 = often, and 4 = almost always).

Before analyzing data, collected surveys were first evaluated for irregularities. Specifically, we looked for surveys from participants who for whatever reason did not provide thoughtful or meaningful responses to all or most of the survey items (e.g., marked "4" for all items or blocks of items) (Barnette, 1999). After reviewing our 331 participants' survey responses, we ultimately excluded data from 24 students (i.e., 7%) from our data pool, and therefore, ended up with 307 (86% complete and 14% incomplete) valid surveys to be analyzed.

A descriptive statistical data analysis was first conducted to provide portraits of students' SR in terms of how often they reported taking up specific self-regulatory approaches including task interpretation (TI), planning strategies to accomplish those specific tasks (i.e., planning strategies – PS), specific strategies used to implement what was planned (i.e., enacting strategies – ES), and monitoring and regulating strategies to revise and make adjustments to what had been done (i.e., monitoring and fix-up – MF). The mean and standard deviation values of each strategic action (i.e., TI, PS, ES, and MF) during each design phase (i.e., problem definition, conceptual design, preliminary design, detailed design, and design communication) and project management (i.e., time, team, and resource management) were calculated. The Friedman test was performed to identify differences across design phases and project management aspects. Follow-up analyses using Sign tests were conducted to examine where the differences occur. Both tests were selected for their abilities to work with data that does not come from the normal distribution, such as the ordinal data (Cohen & Holliday, 1996; Lund Research Ltd, 2013). Furthermore, both tests are selected because they do not assume a symmetrical data distribution shape (Lund Research Ltd, 2013). Since both tests assume the data set is large, they produce asymptotic significance values instead of exact values (IBM Corporation, 2012).

In order to comprehensively describe students' reported SR strategies in completing their capstone engineering design projects, the collected survey data were analyzed in two stages. First, we generated an overview of students' reported use of SR strategies (TI, PS, ES, and MF) within each design phase and for the three project management tasks. Second, we examined students' reported use of strategies associated with each of the design phases as identified in the Dym and Little model (e.g., clarifying objectives as one strategy in the problem definition phase). Since numerous studies reported that engineering students were competent in employing various design and managerial strategies (Atman et al., 2007, 2005; Hotaling et al., 2012; Sobek & Jain, 2007), Friedman and Sign tests analyses were also conducted during this stage to highlight their self-regulation differences.

## 6. Findings

### *6.1 Overview of Self-Regulation During Design Projects*

To create an overview of students' reported SR, we started by considering how much SR students reported during each of Dym and Little's five design phases at a more global level. To begin, we calculated and visually compared the overall amount of SR reported, combining across different SR processes [i.e., an overall mean including task interpretation (TI), planning (PS), enacting (ES), and monitoring/fix-up strategies (MF)]. As we illustrate in Figure 1, we found that students reported relatively similar levels of self-regulating processes across design phases, from detailed design ($M$ = 3.21, SD = .47), to problem definition ($M$ = 3.210, SD = .42); conceptual design ($M$ = 3.14, SD = .42); preliminary design ($M$ = 3.14, SD = .50); and design communication ($M$ = 3.13, SD = .48). In contrast, we did observe different amounts of SR for different aspects of project management (see Figure 1). Students reported the highest levels of SR for managing teamwork ($M$ = 3.35, SD = .44) and time ($M$ = 3.28, SD = .50), followed by resource management ($M$ = 3.18, SD = .45). Consonant with this interpretation, Friedman and Sign tests revealed statistically significant differences in students' reported SR between managing teamwork and resource ($p \leq .001$, Z = -5.103) and between handling time and resources ($p \leq .01$, Z = -2.604).

To explore patterns in more detail, we also looked more specifically at the different types of self-regulating processes being reported in association with each design phase (see Figure 2). Here we found that students reported interpreting tasks (TI) at similarly high levels across all five phases, including during problem definition [$M$ (TI) = 3.26*, SD (TI)* = .56], conceptual design [$M$ (TI) = 3.22*, SD (TI)* = .47], preliminary design [$M$ (TI) = 3.23*, SD (TI)* = .60], detailed design [$M$ (TI) = 3.20*, SD (TI)* = .60], and design communication phases [$M$ (TI) = 3.24*, SD (TI)* = .57]. This suggested that, overall, students were consistently aware of the importance of task interpretation through design activities.

However, the kind and level of other kinds of self-regulating processes reported varied in different design phases. For example, students were more likely to report the use of planning strategies (PS) during problem definition [$M$ (PS) = 3.29*, SD (PS)* = .47] and detailed design [$M$ (PS) = 3.26*, SD (PS)* = .62] than during conceptual design [$M$ (PS) = 3.13*, SD (PS)* = .46], preliminary design [$M$ (PS) = 3.12*, SD (PS)* = .62], or design communication [$M$ (PS) = 3.03*, SD (PS)* = .67]. Consonant with this visual interpretation, Friedman and Sign tests revealed statistically significant differences in students' reported use of planning strategies (PS) between problem definition and conceptual design ($p \le .001$, Z = -4.904), preliminary design ($p \le .01$, Z = -2.944), and design communication ($p \le .001$, Z = -5.813), as well as between detailed design and conceptual design ($p \le .001$, Z = -3.562), preliminary design ($p \le .05$, Z = -2.474), and design communication ($p \le .001$, Z = -4.164) phases. While it could be argued that planning is most relevant during early phases of the design process, still taking a moment to plan approaches based on goals is arguably important through all phases of the design process (e.g., when considering how to present one's design as part of design communication).

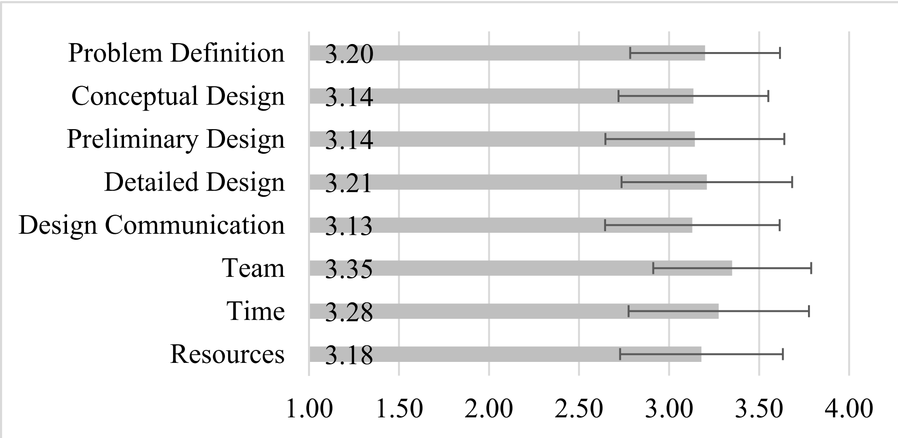


Figure 1. Overall reported self-regulation effort during design phase and project management (N = 229 to 243, mean ranged from 1 to 4)

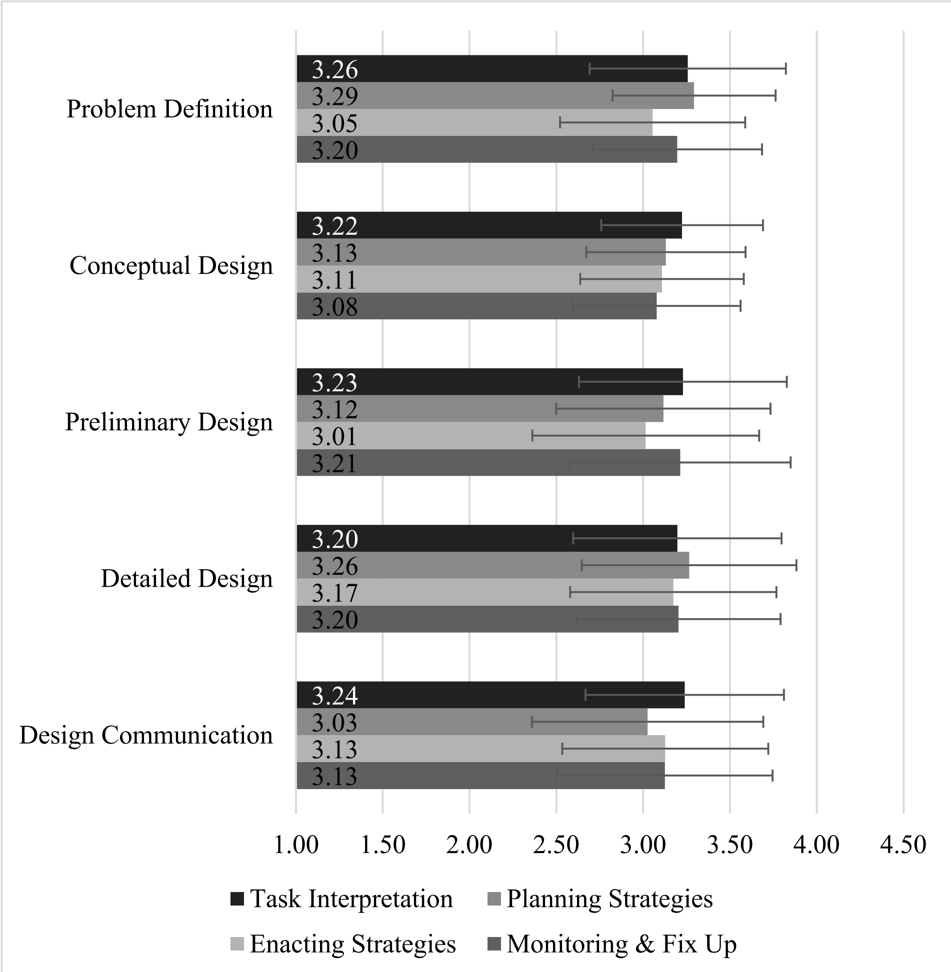


Figure 2. Strategic action in students' reported self-regulation for each design phases (N = 229 to 243, mean ranged from 1 to 4)

Students reported higher levels of enacting cognitive strategies during detailed design [*M* (ES) = 3.17, SD (ES) = .59], design communication [*M* (ES) = 3.13, SD (ES) = .59], and conceptual design [(ES) = 3.11, SD (ES) = .47] than during problem definition [*M* (ES) = 3.05, SD (ES) = .53] and preliminary design [*M* (ES) = 3.01, SD (ES) = .65]. Here again these visual interpretations were supported by finding of significant differences between students' reported use of enacting strategies (ES) between detailed design and problem definition ($p \leq .01$, Z = -2.925) and preliminary design ($p \leq .01$, Z = -2.642), and between design communication and preliminary design ($p \leq .05$, Z = -2.554). This finding suggests that students were not focused as consistently on effective forms of strategy use (as defined in the Dym and Little model) during each phase of the design process.

Finally, students were more likely to report monitoring/fix up strategies (MF) during preliminary [*M* (MF) = 3.21, SD (MF) = .64], problem definition [*M* (MF) = 3.20, SD (MF) = .49], and detailed design [*M* (MF) = 3.20, SD (MF) = .59] phases than during conceptual design [*M* (MF) = 3.08, SD (MF) = .48]. These differences were also statistically significant, within findings of differences in MF strategies between conceptual design and preliminary design ($p \leq .01$, Z = -2.670), problem definition ($p \leq .01$, Z = -2.592), and detailed design ($p \leq .01$, Z = -2670) phases.

Some of these observed patterns can be associated with the nature of design activities. For example, it is not surprising that students would emphasize interpreting task and planning during the problem definition phase, when getting underway with a design task. It also makes sense that they would emphasize monitoring/fix up strategies while engaged in developing designs, when presumably they are using strategies to build, monitor, and refine design solutions. That said, some patterns suggested less awareness or emphasis in how students reported using self-regulating strategies.

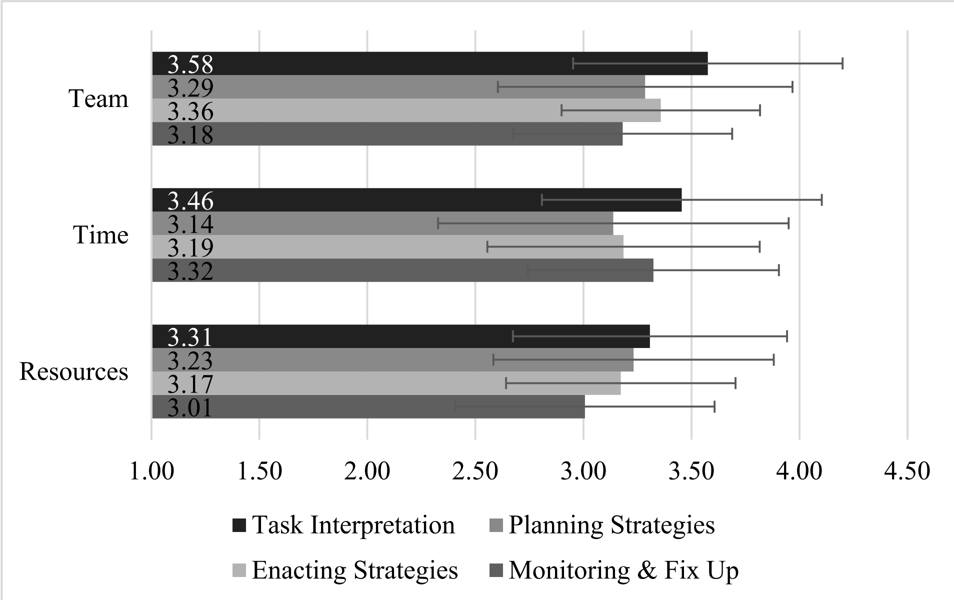


Figure 3. Strategic action in students' reported self-regulation for project management (N = 224, mean ranged from 1 to 4)

Differences in SR patterns were also found in students' project management activities (see Figure 3). Consistent with prior research suggesting that teamwork is among the most difficult aspects of project management (Lawanto et al., 2016; Pant & Baroudi, 2008), students' reported SR of enacting strategies was highest for this aspect of project management [*M* (ES) = 3.36, SD (ES) = .46]. The visual display in Figure 3 elaborates that overall finding by showing how task interpretation was the highest for team than time and resource management activities assessed across the study [*M* (TI) = 3.58*, SD (TI)* = .62]. Students also invested effort in planning [*M* (PS) = 3.29*, SD (PS)* = .68] needed for working with others.

Students were highly focused on task interpretation for all aspects of project management, particularly for teamwork [*M* (TI) = 3.58*, SD (TI)* = .62] and time management [*M* (TI) = 3.46*, SD (TI)* = .65]. Consistent with this visual interpretation, the Friedman and Sign tests revealed statistically significant differences in students' reported use of task interpretation (TI) strategies of those three project management aspects when compared to reported use of the other three self-regulatory processes (e.g., planning strategies) ($p \leq .001$ and Z between -8.387 to -3.260).

Students were less likely to report planning strategies (PS) when managing time [*M* (PS) = 3.14, SD (PS) = .81] than handling team [*M* (PS) = 3.29, SD (PS) = .68] and resources [*M* (PS) = 3.23, SD (PS) = .65].

Interestingly, students were more likely to report using enacting (ES) when managing the team [*M* (ES) = 3.36, SD (ES) = .46] than handling time [*M* (ES) = 3.19, SD (ES) = .63] and resources [*M* (ES) = 3.17, SD (ES) = .53]. We also found significant higher reported use of enacting (ES) and monitoring of students managing their team work than managing their time and resources ($p \leq .001$ or $p \leq .05$ and Z between -5.251 to -2.015).

Students reported the highest level of monitoring/fix up strategies (MF) for time management [*M* (MF) = 3.32, SD (MF) = .58]. The Friedman and Sign tests revealed statistically significant differences in students' reported use of MF on time and team ($p \leq .001$, Z = -3.844) and resource ($p \leq .001$, Z = -6.167) management. This finding is coherent with the idea that students need to carefully navigate, monitor, and adjust their use of time through the design process. In contrast, students invested the least time in monitoring/adjusting their strategies for accessing and using resources [*M* (MF) = 3.01, SD (MF) = .60]. The difference between reported used of MF on resource and team management was also statistically significant ($p \leq .001$, Z = -4.619).

### *6.2 Design Strategies Used in Relation to Self-Regulation*

To further probe into students' SR during design activities, and to elaborate on differences we observed earlier, we conducted analyses to consider students' reported use of SR in relation to the design strategies associated by Dym and Little with each of their phases (see Table 1). Students' reported use of each type of strategy, for each phase, are reported in Table 2a.

Table 2a. Students' reported use of SR associated with design strategies during design projects (N = 229 to 243, Likert scale of 1 to 4; TI = Task Interpretation; PS = Planning Strategies; ES = Enacting Strategies; MF = Monitoring & Fix-Up)

| Design Strategies | TI | | PS | | ES | | MF | | TOTAL | |
|---|---|---|---|---|---|---|---|---|---|---|
| | M | SD | M | SD | M | SD | M | SD | M | SD |
| Design Phase: Problem Definition | | | | | | | | | | |
| Clarify Design Objectives | 3.59 | 0.63 | 3.46 | 0.55 | 3.28 | 0.57 | 3.29 | 0.52 | 3.40 | 0.43 |
| Establish metrics for Design Objectives | 2.81 | 0.84 | 2.77 | 0.76 | 2.92 | 0.78 | 2.84 | 0.75 | 2.84 | 0.56 |
| Identify Constraints | 3.37 | 0.73 | 3.48 | 0.63 | 2.74 | 0.84 | 3.26 | 0.68 | 3.21 | 0.50 |
| Design Phase: Conceptual Design | | | | | | | | | | |
| Establish Functions | 3.52 | 0.61 | 3.30 | 0.69 | 3.14 | 0.64 | 3.13 | 0.70 | 3.27 | 0.47 |
| Establish Requirements | 3.46 | 0.67 | 3.31 | 0.64 | 2.97 | 0.68 | 3.18 | 0.76 | 3.23 | 0.47 |
| Establish Means for Function | 3.24 | 0.74 | 3.18 | 0.69 | 3.07 | 0.71 | 3.03 | 0.65 | 3.13 | 0.51 |
| Generate Design Alternatives | 3.09 | 0.72 | 3.14 | 0.66 | 3.30 | 0.67 | 3.09 | 0.72 | 3.15 | 0.50 |
| Refine and Apply Metrics to Design Alternatives | 2.97 | 0.77 | 3.00 | 0.73 | 3.02 | 0.72 | 2.99 | 0.74 | 2.99 | 0.58 |
| Choose a Design | 3.07 | 0.79 | 2.87 | 0.76 | 3.13 | 0.64 | 3.09 | 0.61 | 3.04 | 0.53 |
| Design Phase: Preliminary Design | | | | | | | | | | |
| Model and Analyze Chosen Design | 3.23 | 0.65 | 3.19 | 0.72 | 2.87 | 0.88 | 3.13 | 0.77 | 3.10 | 0.53 |
| Test and Evaluate Chosen Design | 3.23 | 0.70 | 3.05 | 0.75 | 3.16 | 0.72 | 3.30 | 0.66 | 3.18 | 0.54 |
| Design Phase: Detailed Design | | | | | | | | | | |
| Refine and Optimize Chosen Design | 3.23 | 0.72 | 3.28 | 0.70 | 3.19 | 0.70 | 3.22 | 0.69 | 3.23 | 0.52 |
| Assign and Fix Design Details | 3.16 | 0.73 | 3.25 | 0.73 | 3.16 | 0.72 | 3.19 | 0.66 | 3.19 | 0.51 |
| Design Phase: Design Communication | | | | | | | | | | |
| Document Final Design | 3.24 | 0.57 | 3.03 | 0.67 | 3.13 | 0.59 | 3.13 | 0.62 | 3.13 | 0.48 |
| Project Management | | | | | | | | | | |
| Team Management | 3.58 | 0.62 | 3.29 | 0.68 | 3.36 | 0.46 | 3.18 | 0.51 | 3.35 | 0.44 |
| Time Management | 3.46 | 0.65 | 3.14 | 0.81 | 3.19 | 0.63 | 3.32 | 0.58 | 3.28 | 0.50 |
| Resources Management | 3.31 | 0.63 | 3.23 | 0.65 | 3.17 | 0.53 | 3.01 | 0.60 | 3.18 | 0.45 |

Consistent with first stage data analyses, students reported higher use of task interpretation processes (TI) during all aspects of design. Consistent with this visual interpretation, the analyses of Friedman and Sign tests revealed that students' reported use of task interpretation strategies was significantly higher ($p \leq .001$, $p \leq .01$, or $p \leq .05$) when compared to reported use of the other three self-regulatory processes (see Table 2b).

Somewhat predictably, we found that students reported higher use of task interpretation strategies during early phases of the design (i.e., problem definition and conceptual design) than later ones (i.e., detailed design), particularly for clarifying design objectives and identifying constraints (during problem definition) and for establishing functions and requirements (during conceptual design). That said, it could be argued that students need to attend to task interpretation in all phases, to set goals for their use of strategies relevant to the purpose of each phase (e.g., when communicating their design). Further, it was apparent that students were less likely to engage in self-regulatory processes (as indicated by lower reported use of them) when establishing metrics for design objectives.

In contrast, students seemed to be well-balanced in applying self-regulating processes (i.e., TI, PS, ES, and MF) during the detailed design phase (see Figure 2). During the detailed design phase, the reported use of self-regulatory processes was relatively high (see Table 2a) and the Friedman test showed no significant difference ($p > .05$) between reported SR processes for any of the more specific design strategies associated with this phase (see Table 2b). This finding suggests that students perceived all self-regulating processes as equally relevant and important as students engaged in the strategies associated with the detailed design phase.

Table 2b. Friedman and Sign Tests Analyses of students' reported use of SRs during design project (N = 229 to 243, Likert scale of 1 to 4)

| Design Strategies | Friedman | | Sign Test | | |
|---|---|---|---|---|---|
| | x2 | p | Pair of Strategic Actions | Z | p |
| | | Problem Definition | | | |
| Clarify Design Objectives | 87.266 | 0.000*** | TI-PS | -4.082 | 0.000*** |
| | | | TI-ES | -6.539 | 0.000*** |
| | | | TI-MF | -6.915 | 0.000*** |
| | | | PS-ES | -5.560 | 0.000*** |
| | | | PS-MF | -4.335 | 0.000*** |
| Establish metrics for Design Objectives | 6.248 | 0.100 | | | |
| Identify Constraints | 149.241 | 0.000*** | TI-ES | -8.353 | 0.000*** |
| | | | TI-MF | -2.052 | 0.040* |
| | | | PS-ES | -9.408 | 0.000*** |
| | | | PS-MF | -4.406 | 0.000*** |
| | | | ES-MF | -8.172 | 0.000*** |
| | | Conceptual Design | | | |
| Establish Functions | 69.501 | 0.000*** | TI-PS | -4.177 | 0.000*** |
| | | | TI-ES | -4.778 | 0.000*** |
| | | | TI-MF | -5.528 | 0.000*** |
| | | | PS-ES | -2.873 | 0.004** |
| | | | PS-MF | -3.057 | 0.002** |
| Establish Requirements | 82.646 | 0.000*** | TI-PS | -2.765 | 0.000*** |
| | | | TI-ES | -7.863 | 0.000*** |
| | | | TI-MF | -4.992 | 0.000*** |
| | | | PS-ES | -5.800 | 0.000*** |
| | | | ES-MF | -4.182 | 0.000*** |
| Establish Means for Function | 12.949 | 0.005** | TI-ES | -2.817 | 0.005** |
| | | | TI-MF | -2.379 | 0.017* |
| | | | PS-MF | -2.364 | 0.018* |
| Generate Design Alternatives | 18.017 | 0.000*** | TI-ES | -3.513 | 0.000*** |
| | | | PS-ES | -2.567 | 0.010** |
| | | | ES-MF | -3.607 | 0.000*** |
| Refine and Apply Metrics to Design Alternatives | 1.154 | 0.764 | | | |
| Choose a Design | 24.507 | 0.000*** | TI-PS | -3.307 | 0.001*** |
| | | | PS-ES | -4.521 | 0.000*** |
| | | | PS-MF | -3.234 | 0.001*** |
| | | Preliminary Design | | | |
| Model and Analyze Chosen Design | 33.734 | 0.000*** | TI-ES | -4.864 | 0.000*** |
| | | | PS-ES | -4.122 | 0.000*** |
| | | | ES-MF | -3.660 | 0.000*** |
| Test and Evaluate Chosen Design | 25.246 | 0.000*** | TI-PS | -3.146 | 0.002** |
| | | | PS-MF | -4.402 | 0.000*** |
| | | | ES-MF | -2.791 | 0.005** |
| | | Detailed Design | | | |
| Refine and Optimize Chosen Design | 3.767 | 0.288 | | | |
| Assign and Fix Design Details | 3.857 | 0.277 | | | |
| | | Design Communication | | | |
| Document Final Design | 20.447 | 0.000*** | TI-PS | -3.892 | 0.000*** |
| | | | TI-ES | -2.315 | 0.021* |
| | | | TI-MF | -2.375 | 0.018* |
| | | | PS-ES | -2.657 | 0.008** |
| | | Project Management | | | |
| Team Management | 96.641 | 0.000*** | TI-PS | -5.960 | 0.000*** |

| | | | | | |
|---|---|---|---|---|---|
| | | | TI-ES | -6.414 | 0.000*** |
| | | | TI-MF | -8.387 | 0.000*** |
| | | | PS-MF | -2.126 | 0.033* |
| | | | ES-MF | -5.062 | 0.000*** |
| Time Management | 44.423 | 0.000*** | TI-PS | -5.644 | 0.000*** |
| | | | TI-ES | -5.185 | 0.000*** |
| | | | TI-MF | -3.588 | 0.000*** |
| | | | PS-MF | -2.877 | 0.004** |
| | | | ES-MF | -2.160 | 0.031* |
| | | | TI-PS | -5.644 | 0.000*** |
| Resources Management | 74.127 | 0.000*** | TI-ES | -3.260 | 0.001*** |
| | | | TI-MF | -6.078 | 0.000*** |
| | | | PS-MF | -4.219 | 0.000*** |
| | | | ES-MF | -4.232 | 0.000*** |

*p ≤ .05 ** p ≤ .01 *** p ≤ .001

Another pattern that we noticed was that, in a few cases students reported relatively low use of processes associated with planning (PS) (i.e., when establishing metrics; when refining and applying metrics to design alternatives; when testing and evaluating a chosen design; when choosing a design) or enacting strategies (ES) (i.e., when establishing metrics, identifying constraints, establishing requirements, and modeling and analyzing a chosen design). In those cases, students were often more likely to report a statistically significant higher use of monitoring/fix-up (MF) processes (see Table 2a and 2b). An example is when choosing a design, students reported relatively lower amounts of planning than use of monitoring/fix up strategies (a statistically significant difference). This finding suggests that when students were not applying relevant self-regulating processes for planning or strategy use, they engaged in monitoring and adjusting actions more frequently. It could be that engaging in monitoring and adjusting in those cases, when other self-regulatory processes were being used less frequently, helped students achieve optimal design results. That said, it could be that, had they engaged more proactively in planning, then monitoring/fix up strategies might not have been as necessary.

## 7. Discussion

Despite relatively high reported use of SR processes (i.e., $M \geq 3.0$, which should be interpreted as *often* or *more frequent reported uses of particular SR processes*), our findings identified some important patterns in the kinds and levels of SR reported by engineering seniors. Across our various levels of analysis, we found high reported use of SR in identifying tasks during the design process and project management. This finding was encouraging, given the importance of task interpretation in successful forms of SR. A higher reported use of task interpretation was also evident in prior research with post-secondary students (Atman et al., 2008).

That said, we did find lower reported use of SR in planning, implementing, and monitoring and fix-up strategies. The finding was congruent with what was found in a grades 9-12 engineering design context (Lawanto, 2011; Lawanto et al., 2013). However, as the design phases progressed, students reported more frequent use of monitoring and fix-up strategies, which is coherent with the idea that, as they developed their design, students would need to focus more on monitoring outcomes and adjusting as needed. Still, a relatively balanced self-regulatory profile occurred only during the detailed design phase, suggesting that students were more likely to report engaging in all aspects of SR in the "heart" of design activity (detailing a design). This is problematic because engaging in iterative cycles of strategic action is equally important in design phases before and after the more specific design development. Also, in some cases, if students had attended more to planning, they might not have had to use as many monitoring/fix up strategies.

Finally, students' lower focus throughout on systematically assessing how they were achieving design goals was particularly problematic. Here, one important finding was that, although students engaged in high levels of task interpretation in the problem definition phase overall, these high levels were focused most on clarifying design objectives and identifying constraints. However, a design evaluation checklist to refine the number of possible design solutions was not widely used during the problem-framing phase. The result was consistent lower use of SR on task-interpretation, planning, and monitoring strategies associated with developing an evaluation checklist during the problem-definition design phase. This suggests that students were not aware of the importance of this more detailed strategy as part of engineering design.

When self-regulating their engagement in project management, students were most strongly focused on task interpretation. This was evidenced through the significant attention devoted to understanding task demands, doing their fair share, completing on time, and using proper resources. Enacting strategies and monitoring/fix-up of time, resources, and team-related tasks were reported to a lesser degree. An area of significant concern occurred in students' infrequent efforts to define, update, and adhere to a project budget. Teamwork took the most significant portion of student project management effort, confirming that teams add complexity to design situations. However, this may benefit students because the experience of being part of a team may play a significant developmental role for engineers. An area for further study could be to evaluate the effect on students' ability to function as part of a team through earlier and more frequent project-based learning experiences.

## 8. Limitations

It is important to note that our study used self-reported data on students' SR engagement. As a result, it is important not to interpret our findings as reflecting students' actual engagement in engineering design activities. That said, our use of a self-report instrument was motivated by our goal, not so much to assess students' actions, but rather their perceptions about design activities and how they go about completing them. As a result, we were able to draw valid conclusions about how they were approaching (thinking through and about) design activities as they unfolded over time. Still, future research could usefully collect multiple kinds of measures to dovetail an analysis of what students think about design activities with what they actually do (see Butler & Cartier (2018)) and minimizing bias due to having partial information, such as collecting design artifacts, project schedule, and design journal. Although self-report instruments are not the only available methods for assessing students' SR, they are commonly used (Dinsmore, Alexander, & Loughlin, 2008). In making a further interpretation, the readers must remember that our samples do not accurately represent the engineering student populations. This study is limited by the sample. Also, although we were able to look across responses at three different universities, the number of participants were unequal across each institution.

## 9. Conclusions

Our study revealed that students reported a high utilization of SR in identifying various design and project management task, but lower reported use of follow-up SR strategies (i.e., planning, implementing, and monitoring and fix-up strategies). Since all aspect of SR are equally critical, this finding is problematic. Fortunately, our study also revealed that students reported employing more monitoring and adjusting strategies as they progressed through the design phases.

During problem definition phase, students' skill in establishing metrics for assessing the achievement of design's objectives was relatively low. This was indicated in students' relatively low reported use of self-regulatory (from TI to MF) processes when establishing metrics for design objectives. However, higher reported use of self-regulatory processes were found in refining and applying metrics to design alternative during conceptual design phase. A metric should actually measure the objective that the design is supposed to meet. Dym and Little (2009) argued that good metric is essential in design and should be carefully thought, and the selection of metrics can certainly be improved by collaboration with a well-functioning team. This study found that teamwork took the most significant portion of student project management effort followed by time and resource management.

## 10. Educational Implications

Our study suggests that educators should support students to improve SR in an engineering design project by addressing how they could more fully engage more evenly in self-regulating processes across, as needed, all stages of the design process and project management. This aligns with findings of other studies that suggest that the designer's quality of engagement (i.e., balanced SR) and the number of design phase transitions are correlated with the product quality, especially when solving a complex problem (Atman et al., 2005, 1999). More specifically, a more in depth discussion about the need and use of metrics to evaluate all design objectives may need to be included in all design courses. Furthermore, educators can help students properly scope and frame functions and outcomes so that depth of design is achieved, while considering limitations of budgets, time, and human capital. Those limitations are considered as acceptable criteria of success for an engineering design project (Atkinson, 1999; Jonassen et al., 2006). Providing suggestions and instruction regarding reflective thinking and monitoring of personal and team efforts throughout the design process may be beneficial, as might be timely feedback regarding missing aspects of SR, especially regarding establishing frameworks for evaluating achievement of design goals and schedule creation and adherence. Overall, educators are suggested to design sequences of activities that foster students' development of SR such as creating a scaffold that cues and guides students' engagement in effective forms of SR. Hereafter, they may gradually release responsibility for self-regulation to students as they progressively more independent.

As discussed by Benson and Borrego's (2015) Journal of Engineering Education editorial, we encourage fellow researchers to replicate our study and improve its generalizability, especially by addressing our limitations. Although replication studies are currently underappreciated, they are "essential to moving toward a more reliable and trustworthy understanding of educational environments" (Makel & Plucker, 2014, p. 313). Also, the future replication research can also address the limitations of this study.

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