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Student perspectives on engineering design, decision-making, adaptability, and support in capstone design

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Abstract

This study analyzed how students' sense of support from industry mentors and teammates in a capstone design course was related to their perceived learning regarding engineering design and adaptability when controlling for design self-efficacy and preparedness. An end-of-course survey provided the data for this study and included Likert-type items to measure these six factors as well as open-ended questions regarding students' experience in capstone design. An explanatory, sequential, mixed methods approach (N = 163) was used to assess the importance of industry mentor and teammate support using quantitative data analysis techniques followed by thematic (qualitative) analysis to explain those results.

Likert-type items were analyzed using exploratory factor analyses and resulted in six constructs. Two constructs reflected student perceptions of their learning: engineering design and decision-making skills and adaptability skills. Two forms of support emerged from the factor analysis: industry mentor support and teammate support, and two control variables also emerged: design self-efficacy and preparedness. Support and control variables were then used as dependent variables in regression models for the two learning outcomes. In the regression model for adaptability, teammate and industry mentor support were significantly linked to positive perceptions of adaptability. In the regression model for engineering design and decision making, however, only teammate support was significantly and positively associated with engineering design and decision-making skills. Both control variables were significantly and positively linked to both learning outcomes. Moreover, preparedness significantly interacted with teammate support to impact learning outcomes related to engineering design and decision making and adaptability respectively. This indicated that for students who felt unprepared for the capstone, support was especially important in improving perceptions of what they learned.

Thematic analysis of open-ended questions related to students' learning illustrated that teammate support helped students solve technical challenges and stay accountable to their project goals. Communication and trust among teammates helped students stay adaptable to unforeseen project changes. Meanwhile, industry mentor support helped students navigate ambiguity and tackle unforeseen challenges in their design projects but did not help students address technical details in their designs. Preparedness mediated the relationship between outcomes and support. Students who felt technically unprepared or lacked clear vision of project outcomes benefitted from higher levels of teammate support in engineering design and decision-making and from higher levels of industry mentor support when faced with unexpected challenges in their projects.

Results from this study add to the growing body of literature of industry sponsored engineering design capstones. Specifically, the results have implications for developing (1) evidence-based best practices for industry mentors to best support student learning; (2) incentives that promote supportive team dynamics such as team bonding activities, team charters etc.; (3) strategies that help student feel prepared such as technical and project management workshops; and (4) interventions that enhance students' design efficacy such as project scoping exercises, peer learning, and frequent feedback from teammates and industry mentors.

Introduction

ABET requires that undergraduate engineering program student outcomes emphasize applying "engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors" [1]. Capstone design courses are often designed to address this requirement by providing a significant and often open-ended design experience in the final year of undergraduate education [2]. Industry sponsored capstone programs are one way to deliver this design experience by providing students with the opportunity to work with industry mentors on designing solutions for relevant, real-world problems [3]. According to a 2015 survey of engineering programs in 451 institutions, 79% of the design capstone programs were funded by industry, government, or other external sponsors [4]. Although prevalent, these capstone programs vary widely in how they are implemented [5]. The programs may vary in length [4], assessment [6], number of students enrolled, number of students per team [4], and topics covered [7].

Research on capstone design experiences tend to focus on technical and non-technical skills that students develop during the capstone [8-12]. However, there is a gap in the literature with respect to examining the support students receive from their peers (teammates) and industry mentors as they move through the design process. Teamwork and collaboration with industry mentors are critical aspects of industry sponsored engineering design capstones and impact students' overall design experience. Therefore, it is vital to understand how this support influences student learning in their capstone experience. To that end, this study investigates the relationship between support students received from their teammates and industry mentors and their perceptions about technical and non-technical learning outcomes in an industry sponsored engineering design capstone.

Background

Industry sponsored engineering capstones are usually taught to provide students with a comprehensive engineering design experience in a "real-world" context. These experiences bridge the gap between the undergraduate engineering curriculum and the engineering workplace. A study by Jonassen, Strobel and Lee found that in a real engineering workplace, a vast majority of the problems encountered by engineers are ill-structured and have multiple solution paths [13-15]. In contrast, university students in engineering are taught to solve well-structured problems in the classroom, which often have one "right" answer in the textbook [14,16,17]. Industry sponsored capstones seek to provide students with a taste of real-world engineering by immersing students in the engineering design process contextualized by open-ended problems faced by practitioners in industry. During an industry sponsored capstone, students typically undergo a complete engineering design experience in collaboration with other students on their team and experts such as faculty and industry mentors [18]. Students learn how to develop a solution concept based on sponsor requirements, make design choices and tradeoffs, and evaluate their design in a practical setting [19]. Several studies have investigated frameworks or systems that guide such decision making in design [20-22], design self-efficacy or the ability to complete a design task due to belief in their ability to succeed [23-26], and preparedness to tackle technical and non-technical challenges of the project [27,28]. Other aspects of engineering design that students learn through capstones include systems engineering, ethical concerns related to their design, and professional responsibility.

In addition to advancing *engineering design and decision-making* abilities (so-called "hard" skills), students also improve their non-technical skills (so-called "soft" skills, i.e., skills applicable to multiple career paths) during the capstone design experience [29]. Among the non-technical skills desired by employers are effective communication, delivering high-quality presentations, project planning, teamwork, and time management [30]. In the process of their design work, students learn to communicate effectively with their peers and mentors through multiple modes such as written reports, presentations, in-person work sessions, team meetings and other informal conversations [31]. Student teams also develop skills in project management, which includes project planning, scheduling, and budgeting [32]. The development of such non-technical skills in capstone design courses has been well-documented in literature [29,30,33,34].

In addition to these basic "soft" skills, industry engineers have also identified ability and self-confidence to adapt to rapid or major change as a critical skill for engineers to possess [35]. In fact, design has been theorized as a series of decisions by some [36,37], with one study showing that engineering changes account for nearly one-third of the work effort in some engineering firms [38,39]. Thus, in addition to teaching engineering-specific technical skills and profession-independent non-technical skills, capstone design experiences also offer students the opportunity to learn applied non-technical skills. For example, while change management, an attribute of *adaptability* or a student's ability to remain flexible to and anticipate changes in the project, is a skill that is useful to a wide range of career paths, engineering adaptability specifically involves tools and processes that contextualize broader change management skills to engineering. Sirotiak and Sharma showed that problem-based learning in a senior capstone class led to improvements in students' adaptability and management skills through pre- and post-assessment surveys [40]. In contrast, Leonard, Guanes, and Dringenberg showed that students demonstrated limited improvement in ability to recognize the need for and manage change in decision making, based on interviews of students in a traditional capstone class [41]. Beyond that, Duran-Novoa et al. studied differences in change management between mature engineering firms and young organizations using capstone teams as an example and found that university students are inadequately prepared to identify, manage, propagate, and adapt to changes [42].

The literature on capstone design experiences and research that studies those experiences tend to focus on cognitive outcomes measured by assessing the goodness of design and the quality of deliverables that emerge from the design process [8]. Other studies, although fewer in number, have investigated what are traditionally called "soft" or non-technical skills such as teamwork and communication [9,10]. Still other studies have explored how skills that are supportive of effective engineering design, engineering decision making, and adaptability are developed over the course of capstone design [11,12]. A critical and even lesser studied element affecting the capstone design experience is the level of support of peers and industry in overcoming and adapting to technical and non-technical challenges. In a capstone course implementing the MUSIC model (eMpowerment, Usefulness, Success, Interest, and Caring) of academic motivation [43,44], Jones et al. highlighted how the level of support from teammates can foster or hinder students' engagement in the course [45]. Unlike teammate support, industry mentor support which complements teammate support in industry-sponsored design experiences has not been studied directly in the literature despite the fact that the importance of such industry roles [3,46] and overall mentoring support [47] is well recognized.

To address this gap in the body of knowledge regarding industry-sponsored capstone design experiences, this study developed scales to specifically measure industry and teammate support and studied their relationship to student learning outcomes. Learning outcomes were assessed in two categories: technical and non-technical. The technical learning outcomes focused on *engineering design and decision making* while the non-technical outcomes focused on students' *adaptability* with regard to responding to changes and remaining flexible over the course of the capstone design experience.

Methods

This study analyzed data collected via a survey conducted at a large public research university in an industry-sponsored electrical and computer engineering design capstone, which spanned two quarters (i.e., 20 weeks) during 2021-2022. The study began with an exploratory factor analysis (EFA) to identify constructs that measured students' perceptions of (1) technical and non-technical skills learned (dependent variables), (2) industry and teammate support (independent variables), and (3) design self-efficacy and preparedness (control variables) experienced during the capstone. The factor analysis enabled answering the following research questions:

RQ1: What are the relevant constructs necessary to explore student learning outcomes?
This question was investigated using an EFA of 36 Likert-type questions posed to students in a self-reflection survey administered during the last month of their capstone. EFA allow students' perceptions to be grouped into measures that could then be used as independent and dependent variables in subsequent quantitative analyses. Once the construct validity and reliability of these measures were verified, an explanatory sequential mixed methods approach was undertaken [48] to analyze the survey data. The first phase of such a mixed methods approach was quantitative and led to the following research question:

RQ2: How were (industry and teammate) support linked to student learning outcomes?
Linear regression of the constructs that emerged in RQ1 was conducted to understand links between the independent (support, design elf-efficacy and preparedness) and dependent (learning) constructs. Subsequent qualitative analysis of open-ended responses from the survey were then used to explain the relationships between the independent and dependent variables that emerged in RQ2. This led to one final research question:

RQ3: How and why were student learning outcomes impacted by instructional support?
A thematic qualitative analysis of open-ended responses from the self-reflection responses was used to dive deeper into understanding how and why perceptions of learning were linked with perceptions of support, design self-efficacy and preparedness based on the results from RQ2.

Setting

The study took place in an industry sponsored engineering design capstone course at a large public research university in the U.S. The capstone is a two (ten week) quarter program spanning winter and spring quarters for a total of 20 weeks. In 2021-2022, the program hosted 184 students, 177 of which were electrical and computer engineering majors. Students had an opportunity to select from about 48 projects. Approximately 80% of the projects were sponsored by industry, while the remaining were sponsored by government organizations.

In the first quarter of the capstone, student teams develop a project proposal with their industry mentors. The proposal outlines the purpose of the project, a timeline of goals, and resource projections. After a scope is established, teams move forward to project realization. The teams attend biweekly meetings with teaching assistants (TAs) to report on their progress and share concerns. Students and industry mentors also separately attend an orientation in the beginning of the capstone, which explains the course structure and expectations.

Participants and Procedures

The participants for this study were a cohort of students who enrolled in the industry sponsored engineering design capstone during the 2021-2022 academic year. At the end of Spring Quarter (second quarter of the capstone), students were required to complete an online self-reflection survey regarding their capstone experience. 184 students were surveyed, and 165 responses were received (89.7% response rate). All students were informed that their survey responses would remain confidential. All identifying information was anonymized and kept confidential. Furthermore, no attempt to oversample women or minorities was made in collecting the sample data. All results are cross-sectional.

Instruments

The self-reflection survey contained a total of 41 questions. Questions about learning outcomes relevant to technical skills were developed based on Davis et al.'s conceptual model for capstone engineering design performance and assessment and ABET's student outcomes #3 [1]. Questions relating to non-technical outcomes were adapted from scales developed by Chandler et al. to study entrepreneurs' competencies [49] and scales developed by Keinänen et al. to measure innovation competencies of students in the applied sciences [50].

Table 1: Likert-Scale Survey Items associated with Student Learning Outcomes

Item	Label	Source
Items adapted from Existing Scales		
SE4: I learned how to analyze different designs and selected what we thought would be the most optimal	Systems Engineering	Chandler et al. [49]
A1: I learned how to develop a strategy to best take advantage of resources and capabilities available to us	Adaptability	
A2: I learned how to experiment with different approaches before settling on one		
A3: We learned how to adapt what we were doing to the resources we had		
A4: We learned how to be flexible and took advantage of opportunities as they arose.		
T1: I learned how to effectively collaborate in a team	Teamwork	Keinänen et al [50]
N1: I learned how to use my network to get the information/resources I need	Networking	
Newly Developed Items		
N2: I learned how to reach out to external sources to help me with a problem	Networking	N/A
SE1: I learned how the system development life cycle works- from requirement generation to system conception, design, and evaluation	Systems Engineering	
SE2: I learned to recognize the ethical, environmental and safety implications of our system		
SE3: I learned how to make informed design decisions, while being mindful of their real-world impact.		
A5: At the end of the capstone, I feel more comfortable handling uncertainty in a project	Adaptability	

Items for industry mentor and teammate support were adapted from existing scales validated to measure faculty support [51]. A summary of the close-ended (Likert-type) questions associated with the self-reflection instrument is provided in Tables 1 and 2. All Likert-type items were measured on a 4-point scale from 1: Strongly Disagree to 4: Strongly Agree.

Table 2: Survey Items related to Support, Self-Efficacy, and Preparedness

Description	*Label*	*Source*
Items adapted from Existing Scales		
A6: We allowed the project to evolve as new information was made available	Adaptability	Chandler et al. [49]
G2: I was able to set realistic goals for my project	Goal Orientation	Keinänen et al [50]
G3: I was able to satisfactorily meet the goals I had set		
C1: I was able to come up with new ideas to solve the problems at hand	Creative Problem Solving	Keinanen et al.[50]
C2: I was able to suggest practical solutions to reach a goal		
C3: I am good at coming up with new and imaginative ways to solve the problems I encountered		
P1: I had a clear and consistent vision for what we wanted to end up with, early on in the project	Planning	Chandler et al. [49]
P2: The product/deliverable we delivered is essentially the same one as we had originally conceptualized		
P3: The product/deliverable we delivered is substantially different from what we first imagined		
I1: My industry mentor was available when I needed help	Industry mentor support	Wilson et al. [51]
I2: My industry mentor was willing to spend time with me to discuss issues that are of interest and important to me		
I3: My industry mentor was interested in helping me learn		
I4: My industry mentor cared about how much I learned		
I5: My industry mentor was sufficiently involved in guiding me through all stages of the project		
I6: My industry mentor often asked me whether I had any questions		
I7: My industry mentor treated me with respect		
Newly Developed Items		
PK1: I was able to apply what I had learned in my previous courses to the project	Prior Knowledge	N/A
PK2: I was able to acquire new information that added to my understanding of what I already knew from previous classes		
PK3: I was able to apply the newly acquired information to my project		
G1: I was able to successfully plan tasks to achieve my goals	Goal Orientation	
T2: I was able to effectively communicate with my teammates	Teammate Support	N/A
T3: My team was responsive to my needs		
T4: I tried to ensure that all my teammates felt included		
T5: I felt included and a part of my team		

In addition to Likert-type questions, the survey also contained several short-answer, open-ended questions. These questions are detailed in Table 3 and were designed to elicit information about how students pursued engineering design, made decisions, and adapted to changes along the way.

Table 3: Open-Ended Student Survey Questions

Learning Outcome	*Survey Text*
Engineering Design and Decision-Making	Additional comments on how you solved problems and/or how could you have better tackled problems you encountered
	Additional comments on what helped you achieve your goals and/or how you could have better achieved your goals
	Additional comments on what you learned or wish you had learned about the design process through this course
Adaptability	Additional comments on what you think helped you adapt and be flexible throughout the course
	Additional comments on what could have helped you adapt and be flexible throughout the course

Data Analysis

Since all survey items were either adapted to or newly developed for this capstone setting, an exploratory factor analysis (EFA) was conducted to address RQ1 and develop measures with construct validity and reliability to use in addressing RQ2. Likert-scale data collected from the items in Tables 1 and 2 were analyzed using R (version 4.0.2) and R studio (version 1.3). First, all items were assessed for suitability to an EFA by computing a correlation matrix and removing off-diagonal values greater than 0.9 to prevent redundancies. Next, Bartlett's test of sphericity was conducted to check whether the correlation matrix was an identity matrix. A small *p*-value for this test ($p < .001$) would indicate that the variables are sufficiently correlated and suitable for an EFA. Further, a Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was conducted as it signifies the proportion of an item's variance caused by underlying factors. Therefore, high KMO values are usually desired. Items with KMO values less than 0.5 were removed [52].

To conduct the EFA, a principal component analysis (PCA) was performed on items which were not removed during preliminary tests. The number of factors for PCA was selected based on the number of eigenvalues greater than 1 and the percent variance explained by the factors, with 60% or more being desirable [53]. Items whose variance could not be justified by the factors were identified by computing the communalities. Items with communality less than 0.4 were removed [52]. PCA was repeated until all communalities were greater than 0.4. Once the number of factors was finalized, PCA was repeated with an oblique ("promax") rotation, as items are assumed to be correlated and not orthogonal. Items that significantly loaded (loading > 0.6) onto one factor were retained [54], whereas items that failed to load on any factor or had significant cross loadings were eliminated. The process was repeated until all items were clearly grouped into factors without significant cross-loadings. The internal reliability of the factors was measured using Cronbach's alpha levels. Factors with Cronbach's alpha level greater than 0.6 [53] were deemed suitable for further analysis.

For RQ2, a linear regression model was developed to understand the relationship between student perceptions of their learning and their perceptions of support, design self-efficacy, and preparedness using constructs derived from RQ1. The model was analyzed to identify significant relationships between the dependent (learning outcomes) and independent variables (support, self-efficacy, preparedness).

Finally, a thematic qualitative analysis [55] of the open-ended survey responses in Table 3 was conducted to explore why the independent and control variables of the study were linked to the dependent variables as the regression model from RQ2 indicated. A deductive coding process was used to categorize student responses into perceptions of support, design self-efficacy, and preparedness for each of the learning outcomes. Frequency analyses generated counts within different categories for each learning outcome to provide a clearer picture of the relationship between the dependent and independent variables.

Results and Discussion

The EFA yielded two dependent variables representing learning outcomes, two independent variables (industry support, teammate support), and two control variables (design self-efficacy, preparedness). These six variables were used in the linear regression analysis to answer RQ2 and the results supplemented with qualitative data to answer RQ3.

RQ1: What are the relevant constructs necessary to explore student learning outcomes?

EFA of items representing student learning outcomes yielded the results in Table 4. Only item T1 (Table 1) was eliminated from the preliminary analysis because it had communality less than 0.4. In the subsequent factor analysis of the remaining eleven items, three items were removed because of significant cross loadings (SE4, A1 and A2 – see Table 1).

Table 4: Exploratory Factor Analysis of survey items in RQ1

Items	*Student Learning Outcome*	*Factor Loadings*	
		Factor 1	***Factor 2***
SE1	Engineering Design and Decision-Making	0.0061	**0.8376**
SE2		-0.0759	**0.9213**
SE3		-0.0167	**0.8615**
A3	Adaptability	**0.9622**	-0.2043
A4		**0.8702**	-0.0333
N1		**0.6630**	0.2107
N2		**0.8088**	0.0492
A5		**0.6619**	0.1772
% of Variance		40.3%	30.2%
Cronbach's Alpha		0.82	0.86
Eigenvalues		4.51	1.11

Three items positively loaded onto the first factor which was subsequently labelled "Engineering Design and Decision-Making" and included items associated with the systems engineering aspects of the capstone. The items focused on whether students felt like they learned more about systems engineering, ethical implications of design, decision making. Engineering design and decision-making skills are associated with technical competence. The second factor contained four significantly loaded items associated with adapting to changes in the project scope, dealing with ambiguity, and obtaining information students needed to move forward. This factor was labelled "Adaptability" and refers to a student's ability to manage, remain flexible to and anticipate changes in the project. Unlike close-ended coursework, capstones can be effective tools in helping students become adaptable engineers by exposing them to open-ended real-world problems [56]. Both factors are attributes of top-quality engineers according to prior work [57]. These two factors related to student learning accounted for a total variance of 70.5%, which is above the desired threshold of 60% [53]. Reliability (Cronbach's alpha) for both constructs was above 0.7, which is considered adequate for further study [53].

EFA was repeated for items in Table 2. PCA analyses indicated that one item had communality less than 0.4 (P3 from Table 2) and subsequent PCA analysis with a fixed number of factors resulted in seven items being removed because of significant cross loadings (PK2, PK3, G1, G2, G3, A6 and I7 from Table 2). The remaining items loaded onto four factors: design self-efficacy, preparedness, teammate support, and industry mentor support. Individual loadings are summarized in Table 5. The four factors represented a total variance of 72.1%, in the data which is above the desired threshold of 60% [53]. Reliability (Cronbach's alpha) for all constructs was above 0.7, which is sufficient for further study [53].

Table 5: Exploratory Factor Analysis of survey items in RQ2

Items	*Construct*	*Factor Loadings*			
		Factor 1	***Factor 2***	***Factor 3***	***Factor 4***
C1	Design Self-Efficacy	0.0832	0.1200	**0.8606**	-0.1426
C2		0.0318	-0.0314	**0.8905**	0.0324
C3		-0.0618	0.1214	**0.7625**	0.1602
PK1	Preparedness	0.1308	-0.1781	0.2126	**0.6832**
P1		-0.0464	-0.0569	0.0133	**0.8893**
P2		-0.0517	0.2356	-0.1586	**0.7643**
T2	Teammate Support	-0.1423	**0.8297**	0.1187	0.0763
T3		0.0861	**0.7950**	-0.1413	0.1147
T4		-0.0642	**0.8247**	0.1300	-0.1493
T5		0.0957	**0.8258**	0.0663	-0.0503
I1	Industry Mentor Support	**0.8347**	-0.0273	0.0308	-0.0208
I2		**0.9251**	-0.0872	0.1076	0.0082
I3		**0.9089**	-0.0666	0.1020	-0.0179
I4		**0.8607**	0.1155	-0.1490	-0.0414
I5		**0.9188**	-0.0199	0.0143	0.0110
I6		**0.6126**	0.2133	-0.1457	0.0709
% of Variance		27.6%	18.0%	14.4%	12.1%
Cronbach's Alpha		0.92	0.85	0.85	0.71
Eigenvalues		6.43	2.53	1.55	1.17

RQ2: How were (industry and teammate) support linked to student learning outcomes?
To study the relationship between the dependent variables (two student learning outcomes) and four independent variables (industry mentor support, teammate support, design self-efficacy, preparedness), a linear regression model was developed. First, descriptive statistics were computed for each of the independent and dependent variables (Table 6). The kurtosis and

skewness of all variables fell within the acceptable range of a normal distribution between -7 and +7 and -2 and +2 respectively for all variables [58].

Table 6: Descriptive Statistics of Constructs

Variable	*Mean*	*Median*	*Std Dev*	*Skew*	*Kurtosis*
Engineering Design and Decision-Making	4.22	4.33	0.72	-1.17	2.13
Adaptability	4.38	4.6	0.63	-1.21	1.75
Design Self-Efficacy	4.39	4.33	0.59	-0.84	0.94
Preparedness	3.87	4.00	0.84	-0.57	-0.29
Teammate Support	4.46	4.75	0.67	-1.45	-1.42
Industry Mentor Support	4.39	4.67	0.73	1.99	2.13

To ensure that none of the assumptions of multiple linear regression were violated, model residuals versus independent variables were plotted to check for any violation against linearity and heteroscedasticity. Normal Q-Q plots were examined to check for violation of normality [53]. None of the above-mentioned assumptions—linearity, heteroscedasticity, and normality were violated. The results of the two regression models (one for engineering design and decision-making and one for adaptability) are summarized in Table 7.

Table 7: Linear Regression Results

Predictors	Estimates	Standard Error
Student Learning Outcome #1: Engineering Design and Decision-Making		
(Intercept)	-2.0439	1.069
Industry Mentor Support	-0.006	0.065
Preparedness	1.025	0.300***
Teammate Support	0.781	0.242**
Design Self-Efficacy	0.352	0.079***
Preparedness*Teammate Support	-0.155	0.065*
R^2/Adjusted R^2	0.517/0.502	
Student Learning Outcome #2: Adaptability		
(Intercept)	-1.059	1.069
Industry Mentor Support	0.505	0.171**
Preparedness	0.644	0.22**
Teammate Support	0.248	0.062***
Design Self-Efficacy	0.312	0.066***
Preparedness*Industry Mentor Support	-0.101	0.049*
R^2/Adjusted R^2	0.564/0.549	

* p < .05, ** p < .01, *** p < .001.

The final model for *engineering design and decision-making* had an adjusted R^2 of 0.50, indicating that the independent variables and interactions between them collectively explained 50% of the variance in the data. All independent variables were significantly and positively linked to *engineering design and decision-making* except for industry mentor support.

The final model for *adaptability* had an adjusted R^2 of 0.55 indicating that the independent variables and interactions between them collectively explained 55% of the variance in the data. All independent variables were significantly and positively linked to *adaptability*.

Two significant interaction effects between the independent variables were observed. In the first model (for *engineering design and decision making*), interactions between preparedness and teammate support were significant, indicating that for students who did not feel well-prepared for the project, teammate support played a larger role in their engineering design and decision-making skills. Similarly, in the second model (for *adaptability*), the interaction between preparedness and industry support was significant, indicating that industry mentor support has a stronger impact on adaptability skills when students felt less prepared for their projects.

RQ3: How and why were student learning outcomes impacted by instructional support?
Deductive coding in the thematic analysis of the qualitative data was done according to four themes corresponding to the four independent variables in the regression analysis. Frequencies of the four themes are summarized in Table 8 as they related to the two themes associated with student learning outcomes used in the quantitative analysis. Teammate support and preparedness were the most cited factors that helped students through *engineering design and decision-making*, while for *adaptability*, design self-efficacy and industry mentor support led the way.

Table 8: Frequency Analysis of Qualitative Themes

Theme	**Frequency (Mentions)**	
	Engineering Design and Decision Making	*Adaptability*
Industry Mentor Support	31	14
Design Self-Efficacy	39	14
Teammate Support	48	11
Preparedness	42	13

Why Teammate Support Matters
Two aspects of *engineering design and decision-making* prominently emerged as needing teammate support: solving technical problems and achieving goals. Students emphasized the value of a strong organizational structure, effective project management, and communication among team members, as exemplified here:

> "I think I helped our team achieve our goals by being an effective team manager and keeping the team organized and suggesting practical goals."

Technical problem solving also benefitted from strong teammate support. For instance:

> "I was stuck with the appropriate deep learning model for my end of things. Upon discussing with everyone within the team, we came up with different models to try out like fast rcnn, d2go, yolo. Also, we had problems with setting up Bluetooth in Arduino. All of us go together in the lab and resolved the problem."

In addition to problem solving, students also looked to their teammates for brainstorming ideas, balancing pros and cons of different designs and planning for engineering tasks:

> "I learned a lot about how design process works, such as initial brainstorming, working with the team to determine what design is best (pros and cons of each and how to fix them down the line after we get a working rough prototype out), etc."

Although mentioned less frequently, students also relied on teammate support to improve adaptability. Students emphasized the value of having good communication with their teammates in making the design journey easier, especially when facing and adapting to challenges. In short:

> "Effective communication made it easier to adapt and be flexible. Trusting my teammates helped me take challenges head on rather than getting frustrated when things were not going my way."

Clearly, during the design process, a student's team was their best resource to solve technical problems, come up with new ideas, ensure that goals are being achieved on time, and navigate unforeseen changes in their project scope. This result is a clear call for capstone instructors to pursue additional and improved strategies to build team support.

Why Industry Mentor Support Matters

Two aspects of industry mentor support emerged as being prominent to students' perceptions of *adaptability*: the mentors' (1) technical feedback, and (2) flexibility to changes. Students stated that being able to frequently ask technical questions and have access to expert advice helped them adapt to different changes, and effectively solve problems:

> "Having an industry mentor that was so involved and was able to actively give us feedback helped a lot when it came to flexibility. When we wanted to try something out of the box our industry mentor could quickly approve and give feedback on those ideas that weren't originally planned."

Flexibility on the mentor's part made students feel more comfortable in exploring the problem space and altering aspects of the project that students deemed infeasible. Negative aspects of industry mentor support also forced students adapt, for instance:

> "We got used to having to adapt in the project because our industry mentors would often have to take time giving us access to various things and it forced us to change our focus for the week."

However, delayed industry mentor support was not a learning experience for all students:

> "We in a sense lost upwards of 7-8 weeks of time due to a bunch of delays and miscommunications and internal issues on the company end that caused our project to be in much worse shape than anticipated."

Therefore, there is a fine line between when an industry mentor's lack of timely support can be a learning experience versus when it may result in inferior project outcomes.

While not statistically significant, examples of industry mentor support impacting students' perceptions of *engineering design and decision-making* emerged in the qualitative responses. Students looked to industry mentors for "high-level" support instead of details on solving technical problems and expressed how well-defined expectations from the mentor allowed them to design with more clarity:

> "The company came into the project with a fairly set idea for what they wanted to see so we didn't make many big picture decisions about what our device would do, however we had lots of implementation decisions for how exactly to accomplish the overall goals."

For *engineering design and decision-making*, mentor support was not as influential in solving technical problems or making detailed design decisions, which is likely why it was not significantly linked to perceptions of *engineering design and decision-making skills* in RQ2. However, early support from the mentors in defining a clear vision of the project goals can aid students in making technical decisions more easily. This calls for the development of best practices to help mentors support student learning so that students can take ownership of their design experience without getting lost in the process.

How Preparedness Makes a Difference

Two aspects of preparedness emerged as being important to students' perceptions of *engineering design and decision-making* and *adaptability:* (1) technical preparedness, and (2) project plan preparedness. Students who felt more prepared for their project were also able to organize their team's direction more effectively. This demonstrates how preparedness mediates the relationship between teammate support and engineering design and decision-making. For example:

> "As I had worked on similar problem of robot collaboration before, I was aware of the challenges and had the Birdseye view of the problem/modules. This helped in ensuring stable overall progress of the project and more profound brainstorming/scope discussion."

In the case of *adaptability*, one student remarked how prior technical experience with student engineering clubs helped them better adapt to uncertainties in the project. Additionally, students seemed more comfortable adapting to changes later in the project if they had clarity about the project goals earlier on. Industry mentor support emerged as being vital to preparing students to adapt to unforeseen changes by providing a concrete vision of the project goals.

From both quantitative and qualitative results, it is evident that preparedness is important to students' perceptions of both *engineering design and decision-making* and *adaptability* skills. Capstone instructors can better prepare students by providing appropriate educational resources during the capstone and developing best practices for industry mentors to help students appropriately scope project goals.

How Design Self-Efficacy Makes a Difference

Students' ability to self-learn and apply new knowledge to solve problems emerged as being key to positive perceptions of what they learned about *engineering design*, as exemplified by one student:

> "I feel like initially the project scared me and I questioned my ability to handle it, but eventually I realized that even if I don't know some of the software and concepts that we need to use, I can learn them and contribute to the progress of the project."

Students mentioned how they pivoted their problem framing and/or accessed different online resources to achieve project goals and overcome technical challenges and were appreciative of what they learned about executing an open-ended, real-world engineering project.

> "I learned how to create system architecture, conceptual models, simulation to better design experiments that help progress goals under hardware, environment constraints."

A prominent aspect of design self-efficacy that impacted students' perceptions about *adaptability* was information and resource gathering. When students did not receive support or expertise within their own teams, they adapted by actively seeking information outside their immediate reach (forums, other capstone groups, open-source communities) to find solutions. However, some students expressed frustration at self-learning and a lack of teammate or industry mentor support. The burden of self-learning led students to feel of stressed and worry that they might not be able to deliver on their project goals.

Given the importance of design self-efficacy in enhancing students' belief that they can be successful in their capstones, instructors should consider devising strategies to boost students' design self-efficacy. This may include helping students scope tasks that are challenging yet attainable and can bolster students' sense of mastery, facilitate peer learning, and create frequent feedback loops with teammates and industry mentors [59].

Limitations

The present study offers a unique contribution to the engineering capstone literature by focusing on the role of support, design self-efficacy and preparedness on learning outcomes. The study draws on a capstone design experience at a single institution and the generalizability to other academic settings may be limited. A limitation of the qualitative analysis in this study is that the analysis and interpretation are based on the subjectivity of the researcher [55]. But the multiplicity of open-ended questions served as a form of triangulation to render credibility to the findings of the study. Another limitation is the positionality of one of the authors as a teaching assistant for the capstone program during the setting being studied. Her interpretation of students' design experience is prone to some "biases, dispositions and assumptions regarding the research" [55] that may have influenced the interpretation of the themes. However, despite these limitations, this study offers rich insight into how teammate and industry mentor support influence students' perceptions of the technical and non-technical skills they gained during the capstone.

Implications

This study underscores teammate and industry mentor support as critical elements of students' capstone design experience. Design self-efficacy and preparedness play an important role in controlling for the impact of support on learning. Therefore, capstone instructors should prioritize developing structured ways to facilitate teammate and industry mentor support. Evidence-based best practices should be developed, which enable industry mentors to support students while fulfilling their goals and motivations for participating in capstone programs. Moreover, capstone instructors should consider developing interventions that help students feel supported by their teammates through alignment in expectations, expertise, and communication.

Preparedness and design self-efficacy also emerged as being significant in influencing students' perceptions of what they thought they learned about engineering design and adaptability. This has multiple implications for instructors. The first is to ensure that students feel technically supported throughout the capstone by having the appropriate educational resources and help. The second is to impart effective collaborative project planning and management strategies so that students can develop a clear understanding of their project in conjunction with their teammates and industry mentors early in the project cycle. Lastly, strategies to enhance students' design self-efficacy are important and can include helping students appropriately scope tasks, learn from their peers and provide constructive feedback on performance.

Conclusions

This study has examined the relationship between sense of support in a capstone design course and students' perceptions about engineering design and adaptability when controlling for design self-efficacy and preparedness. The results largely confirm the significance of support, self-efficacy, and preparedness in shaping students' perceptions about a positive design capstone experience. All elements of support and control factors were significant in positively influencing students' perceptions of positively adapting to changes in their project. Similarly, all but industry mentor support emerged as positively influencing students' perceptions of what they learned about engineering design and decision-making. This was because students would only seek high-level support from their industry mentor for solving detailed technical challenges. Moreover, preparedness was key in mediating teammate support and industry mentor support for perceptions of engineering design and adaptability respectively. The qualitative analysis supported the finding that many students did not feel as well prepared for their capstone and relied on industry mentor and teammates to support engineering design activities and help adapt to unforeseen changes in the project scope. Future work can investigate ways of operationalizing the constructs from this study to capstone settings in other disciplines and institutions, so that common best practices and interventions can be designed to support students in industry-sponsored engineering capstones.

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