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Is senior design preparing engineering students for a post-academic mindset?

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Background

The overarching goal of engineering capstone design programs is to prepare students for entering the workforce. Capstone design courses are typically project-based, where students work in teams to address a "customer-provided" problem and develop real working solutions. This type of project-based learning requires that students synthesize knowledge and apply skills to an open-ended design problem. The open-ended nature of "customer-provided" problems that students encounter in capstone design courses contrasts with the structured and constrained "instructor-provided" problems seen in their earlier coursework [1], [2]. Solving complex, unstructured problems is an essential skill for a working engineer, but it requires a different skillset than that which is needed to solve the standard textbook problems typically seen in classrooms [2]–[6]. Solutions to textbook problems are formulaic [2], whereas solutions to open-ended problems are unpredictable due to a multitude of factors (e.g., incomplete information, unanticipated problems, multiple and/or conflicting goals) [2], [3], [7].

Unsurprisingly, studies of senior design programs have shown that significant maturation occurs for students during their senior design experience [1]. This maturation, which has been referred to as the transition from an instructor-directed learner to a self-directed learner [8], can be a traumatic experience for students. Students operate under an "academic mindset" for most of their undergraduate education, trusting that their instructors are omniscient and that there is one correct approach to solving any given problem. A successful capstone design experience requires that students leave behind these notions. Based on our observations of students in our engineering program, some students embrace a "post-academic" mindset, while others remain in an "academic" one. The former gain confidence as they tackle an open-ended design challenge, while the later struggle to solve complex problems with multiple potential solutions and experience discomfort upon realizing their instructors are not omniscient.

In most industries, it is well understood that a big component of any engineer's work is documentation [9]. However, we repeatedly observe our students not understanding the importance and relevance of documentation, instead perceiving it as additional, unnecessary work that detracts from time that could be spent on the design process. If student perception of documentation and the design process is disjointed and incohesive, it becomes difficult for instructors to facilitate students' development of the skills necessary for engineering careers.

During the 2022-23 academic year, our 30-week capstone design course sequence was co-taught by an industry-experienced instructor with ~30 years of experience in the medical device industry and an academic-experienced instructor. The instructors had equal responsibility and involvement in teaching the course (e.g., co-teaching lectures, meeting with every student team on a weekly (or biweekly) basis, attending sponsor-student team meetings, reaching out to sponsors for feedback). Working in collaboration, the co-instructors refreshed the course structure to address two reoccurring themes observed in previous cohorts: (1) students struggling to adopt a "post-academic" mindset; and (2) students not perceiving design documentation as integral to the design process.

The course was restructured to reflect a semi-imaginary consulting engineering firm, "Mountain Top Engineering", where the instructors acted as the firm's CEOs, the students acted as the firm's engineering associates, and the firm's customers were external industry or non-profit sponsors. (Note: all design projects were funded by external industry or non-profit sponsors.) While industry sponsored multidisciplinary project teams for senior design experiences is not new [10], [11], we thought that integrating an active, role-playing approach would instill a deeper level of professional responsibility in our student cohort and add additional motivation for delivering a functional prototype to the "customer".

To create organization and relevance for the associates, three pillars of operation, each representing a different dimension of project delivery, were scaffolded throughout the course content. All design documentation and presentations were introduced to students within the framework of these three pillars (Figure 1).

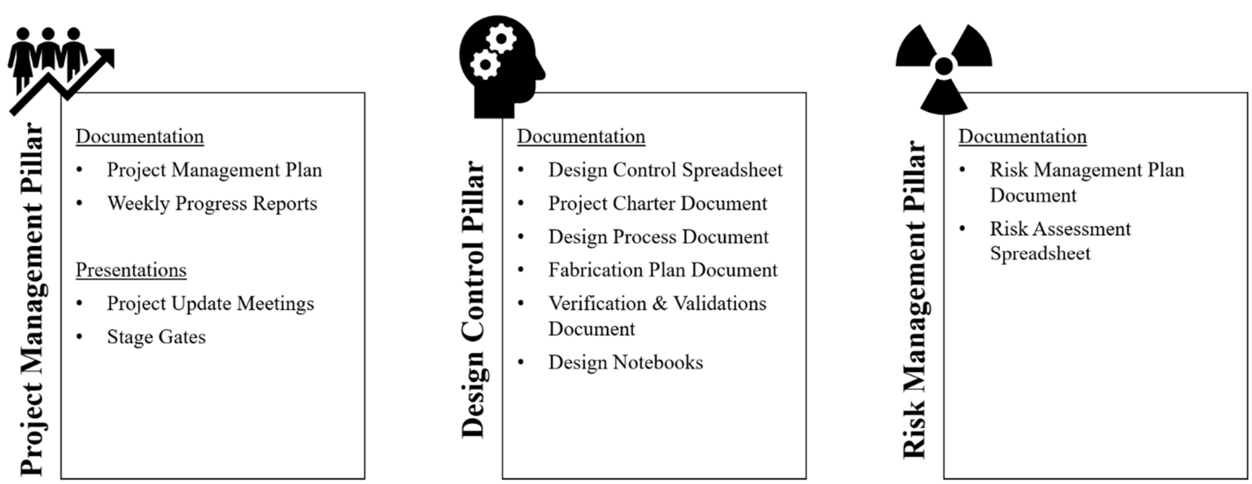

Figure 1: Three pillars of operation were scaffolded through the 30-week course series. The deliverables associated with each pillar were presented to students during the first week of the course. Pillars were assigned a unique slide tag that was used in subsequent lecture materials to indicate the relevant pillar(s) of operation to the topic in discussion.

The *Project Management Pillar* focused on developing a project-specific schedule, assigning individual tasks, and managing expenses within a project-specific budget. The instructors provided deadlines for high-level milestones (i.e., specific interactions with project sponsors around project updates and stage gate reviews) (Figure 2), but student teams were responsible for developing and working to their own project-specific schedule to meet the prescribed milestones. Starting from the business stage gate model, students developed a list of tasks necessary to reach the high-level milestones, estimated durations for those tasks, considered predecessors and successors, formed an initial plan, and assigned individual responsibilities. To facilitate this process, the instructors provided templates for the project management plan document, weekly progress reports, and project update meetings.

The *Design Control Pillar* focused on gathering customer requirements, developing design requirements, and creating and verifying design solutions. After identifying customer requirements during an initial kick-off meeting with their sponsor, students developed appropriate design requirements to meet their customer's needs, and then moved through the iterative design process to create and verify their developed solutions. This iterative process culminates in the development of a complete fabrication plan and final prototype (Figure 3).

Teams were provided with a design control spreadsheet template to assist with requirements traceability. This "master" spreadsheet captures traceability throughout the design process (customer requirements to final prototype). Teams also developed a concept of operations (CONOPs) diagram, a system diagram, and a functional decomposition diagram. In the context of our course sequence, these diagrams were intended to help students identify and organize the systems/subsystems necessary for solving an open-ended customer-provided problem, thus making links to potential design solutions more manageable and less overwhelming.

The *Risk Management Pillar* focused on identifying project and product risks, assessing the potential severity of those risks, and developing appropriate mitigation plans. Following the expertise of the industry-experienced instructor, students considered the probability of occurrence (P) and potential harm or severity (H) for each risk. Overall risk was determined by the product of P×H. The instructors provided a risk assessment spreadsheet template to assist student teams in tracking, assessing, mitigating, and retiring their project and product risks.

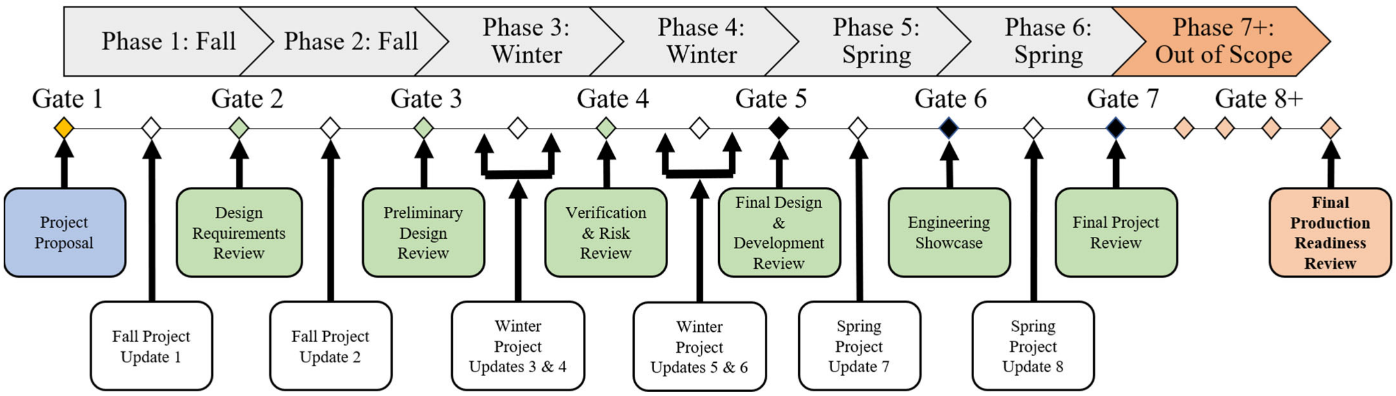

Figure 2: High-level project milestones were modeled after business Stage Gates. These milestones were the only instructor-provided deadlines in the course sequence.

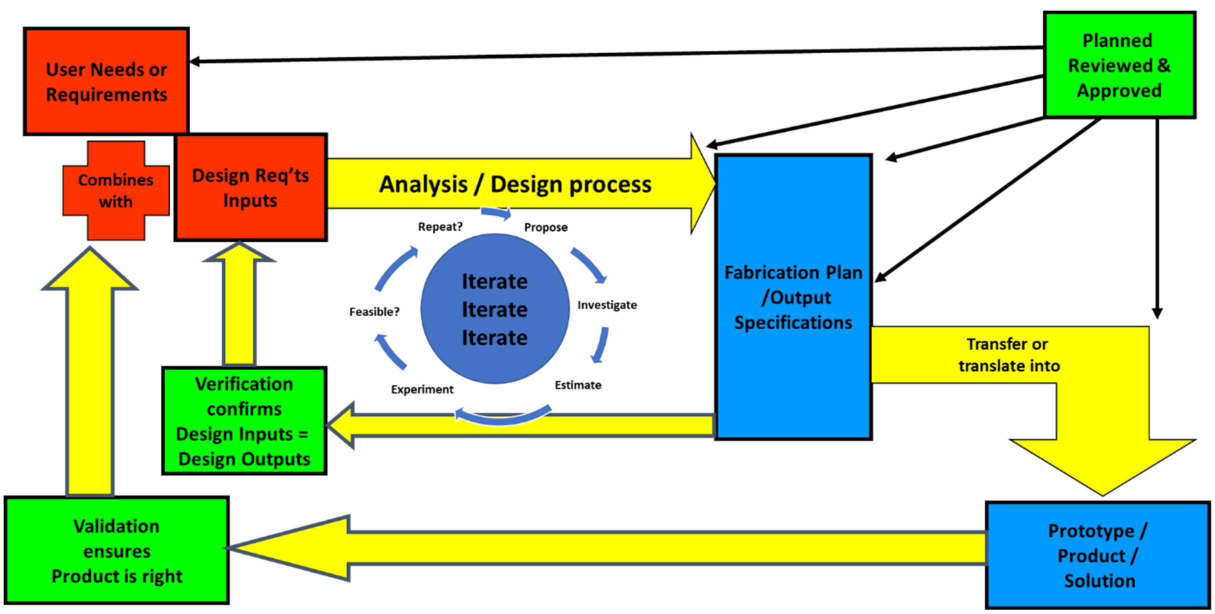

Figure 3: Conceptual design process cycle including the inner cycle of iterations required often in design prior to completion of a final fabrication plan and prototype construction. (adapted from [9] and used by others [12]).

The purpose of this study was to determine if our course restructure, specifically the introduction and scaffolding of the three pillars of operation and their associated documentation templates, resulted in our students becoming more confident in their ability to solve open-ended problems

with multiple potential solutions (i.e., were we able to instill a “post-academic” mindset within our students?). We specifically aimed to answer the following questions:
(1) Do students perceive senior design as a course for credit or a project experience?
(2) Do students perceive the 3 pillars of operation as useful/relevant to the capstone course?
(3) Do students perceive the 3 pillars of operation as useful/relevant to their future career?
(4) Do students feel confident that senior design will prepare them to be a working engineer when they graduate?

We hypothesized that student's mindset (“academic” vs. “post-academic”) would be linked to their perceptions of senior design (course for credit vs. project experience) and the three pillars of operation (relevant vs. not-relevant to the course/their future career).

Methods

IRB approval was obtained to invite our capstone students from two consecutive cohorts (academic years 2022-23 and 2023-24) to complete a voluntary, anonymous, online Qualtrics survey. For each cohort, the survey was approved to be administered twice: once at or near the beginning of the course sequence and once at the end. The survey was designed to take approximately 5-10 minutes to complete. Students were not compensated for participation. The survey link was sent to students by way of an online learning management system announcement. Students who agreed to participate were prompted (not forced) to answer 19 survey questions. A five-point Likert scale was used for most questions. Any questions deviating from a five-point Likert scale are noted in the results.

In addition to pre-course student perception data, intermediate mid-course data were collected in the first year to support this study. Differences between pre-course and mid-course student perceptions were evaluated with a paired two-sample t-test (significance level: $p<0.05$). Students will be asked to repeat the survey at the end of the academic year. We plan to compare pre-course and end-course student perceptions over several cohorts.

Results

Our results show a slight shift in student perception towards viewing senior design as a project experience instead of as a course needed for graduation (Table 1, question 1a). Similarly, there was a slight shift towards students seeing themselves as associates of our semi-imaginary firm (Table 1, question 1d). However, neither of these changes was statistically significant. There were also no significant changes in how students viewed importance of following the course curriculum and completing instructor provided assignments (Table 1, questions 1b and 1c). Our results indicate that the students became significantly more familiar with the three pillars of operation as the course progressed (Table 2). Student perceived relevance of the three pillars of operation to both the course and their future careers grew as the course progressed, but this change was only significant for the risk management pillar (Tables 3 and 4). There was also a general trend towards students building confidence as they progressed through the senior design experience, but these changes were not significant (Table 5).

Table 1: Survey data reflecting student perception of the senior design experience. Question 1a was answered on a 7-point scale (1 = entirely a course for graduation, 7 = entirely a project experience, 4 = equally a course for graduation and a project experience). Questions 1b-1d were answered on a 5-point Likert agreement scale (1 = strongly disagree, 5 = strongly agree).
* indicated differences between pre-course and mid-course perceptions were significant for p<0.05.

Survey Question	**Pre-Course Perception (mean ± std dev)**	**Current Perception (mean ± std dev)**	**p-value**
1a: Do you think of Senior Design primarily as a course you need for graduation or as a project experience? *(7 point scale)*	3.25 ± 1.36	4.33 ± 1.67	0.065
1b: I will successfully deliver my project to my sponsor if I follow the course curriculum and do the assignments as given to me by my instructors.	3.67 ± 1.12	3.09 ± 1.38	0.29
1c: I will successfully get a good grade in this course if I follow the course curriculum and do the assignments as given to me by my instructors.	4.00 ± 1.00	4.27 ± 0.79	0.43
1d: I see myself as an associate of Mountain Top Engineering - Class of 2023 LLC	3.14 ± 1.07	4.00 ± 1.73	0.078

Table 2: Students were asked to indicate their level of familiarity with the three pillars of operation on a five-point scale (1 = not at all familiar, 5 = extremely familiar agree). * indicated differences between pre-course and mid-course perceptions were significant for p<0.05.

Survey Question	**Pre-Course Perception (mean ± std dev)**	**Current Perception (mean ± std dev)**	**p-value**
2a: What is your familiarity with the following pillars of operation?			
Project Management Pillar	2.45 ± 1.30	3.73 ± 0.65	<0.001*
Design Control Pillar	2.36 ± 1.36	3.73 ± 0.79	<0.001*
Risk Management Pillar	2.55 ± 1.29	3.55 ± 0.93	<0.001*

Table 3: Survey questions and responses directed towards the research question 'Do students perceive the 3 pillars of operation as useful/relevant to the capstone course?' * indicated differences between pre-course and mid-course perceptions were significant for p<0.05.

Survey Question	Pre-Course Perception (mean ± std dev)	Current Perception (mean ± std dev)	p-value
3a: Are the following pillars of operation relevant to the senior design course?			
Project Management Pillar	3.38 ± 0.92	3.88 ±0.83	0.17
Design Control Pillar	3.50 ± 0.93	4.00 ± 0.76	0.10
Risk Management Pillar	2.88 ± 0.99	3.88 ± 0.83	0.001*
3b: Are the following (project management) skills relevant to the senior design course?			
building Gantt Charts	2.14 ±1.46	3.57 ±1.27	0.016*
making task assignments	3.00 ±1.00	4.43 ± 1.13	0.016*
estimating activities needed for a project	2.86 ±1.07	4.29 ± 1.11	0.016*
estimating project costs	3.14 ± 1.35	4.14 ± 0.69	0.086
preparing written project updates	3.29 ± 0.95	3.71 ± 1.11	0.20
preparing and presenting project updates	3.71 ± 0.76	4.29 ± 0.49	0.10
presenting Stage Gate reviews	3.57 ± 0.79	4.29 ± 0.76	0.094
3c: Are the following (design control) skills relevant to the senior design course?			
writing design requirements	2.71 ± 1.25	4.14 ± 1.07	0.016*
keeping a design requirements traceability matrix	3.71 ± 0.76	4.43 ± 0.79	0.047*
managing a design control spreadsheet	2.71 ± 1.25	3.57 ± 1.27	0.045*
creating a concept of operations	2.86 ± 1.22	3.71 ± 1.11	0.045*
drawing a systems diagram	3.57 ± 0.79	4.00 ± 1.00	0.29
defining a functional decomposition	3.57 ± 0.79	4.14 ± 0.90	0.10
defining a method of verification	3.43 ± 0.79	4.00 ± 0.82	0.10
using methods of estimation	3.00 ± 1.00	3.86 ± 1.07	0.045*
keeping a design notebook	2.86 ± 1.07	3.71 ± 1.11	0.017*
3d: Are the following (risk management) skills relevant to the senior design course?			
making a risk management plan	2.73 ± 1.11	3.57 ± 1.27	0.045*
using a risk assessment spreadsheet	2.71 ± 1.11	3.43 ± 1.27	0.047*
identifying mitigation plans	3.00 ± 1.15	3.57 ± 1.27	0.17

Table 4: Survey questions and responses directed towards the research question 'Do students perceive the 3 pillars of operation as useful/relevant to their future career?' * indicated differences between pre-course and mid-course perceptions were significant for p<0.05.

Survey Question	**Pre-Course Perception (mean ± std dev)**	**Current Perception (mean ± std dev)**	**p-value**
4a: Are the following pillars of operation relevant to your future career (i.e. post-academic experience)?			
Project Management Pillar	3.45 ± 0.82	3.64 ± 1.12	0.34
Design Control Pillar	3.45 ± 0.93	3.73 ± 1.35	0.39
Risk Management Pillar	3.00 ± 0.89	3.82 ± 1.25	0.042*
4b: Are the following (project management) skills relevant to your future career?			
building Gantt charts	1.67 ± 0.71	3.11 ± 1.17	<0.01*
making task assignments	3.22 ± 0.97	4.22 ± 1.09	0.017*
estimating activities needed for a project	3.33 ± 0.71	3.89 ± 0.78	0.05*
estimating project costs	3.67 ± 1.00	4.00 ± 0.87	0.20
preparing written project updates	3.00 ± 0.71	3.22 ± 1.30	0.51
preparing and presenting project updates	3.56 ± 0.72	3.89 ± 1.17	0.20
presenting stage gate reviews	3.00 ± 1.41	3.78 ± 1.48	0.065
4c: Are the following (design control) skills relevant to your future career?			
writing design requirements	2.88 ± 0.64	4.50 ± 0.76	<0.005*
keeping a design requirements traceability matrix	3.13 ± 0.64	4.25 ± 1.04	0.015*
managing a design control spreadsheet	2.00 ± 0.76	3.38 ± 1.41	0.008*
creating a concept of operations	2.00 ± 1.07	3.25 ± 1.58	0.028*
drawing a systems diagram	3.25 ± 0.89	3.88 ± 0.83	0.14
defining a functional decomposition	3.38 ± 1.06	3.88 ± 0.83	0.23
defining a method of verification	3.25 ± 0.89	3.63 ± 0.92	0.28
using methods of estimation	2.38 ± 0.92	3.25 ± 1.28	0.021*
keeping a design notebook	2.38 ± 0.92	3.63 ± 0.92	0.005*
4d: Are the following (risk management) skills relevant to your future career?			
making a risk management plan	2.50 ± 0.76	3.50 ± 1.20	0.018*
using a risk assessment spreadsheet	2.38 ± 0.92	3.25 ± 1.28	0.021*
identifying mitigation plans	3.38 ± 0.74	4.13 ± 0.64	0.048*

Table 5: Survey data used to evaluate whether students feel confident that senior design will prepare them to be a working engineer when they graduate. Questions were assessed using a 5-point Likert scale (5a-e: 1 = strongly disagree, 5 = strongly agree; 5f: 1 = extremely negative, 5 = extremely positive). * indicated differences between pre-course and mid-course perceptions were significant for $p<0.05$.

Survey Question	**Pre-Course Perception (mean ± std dev)**	**Current Perception (mean ± std dev)**	**p-value**
5a: I am confident that senior design prepares me for my future career as an engineer.	3.43 ± 1.27	4.00 ± 1.53	0.17
5b: I am confident that I could deliver my project without instructor defined deliverables.	2.86 ± 1.57	3.86 ± 1.07	0.11
5c: I think the design process is fun.	3.71 ± 0.95	3.71 ± 1.38	1.00
5d: The course deliverables are important to the successful completion of my project.	3.14 ± 1.35	3.71 ± 1.50	0.28
5e: Documentation is integrally important to the design process.	3.14 ± 0.69	3.86 ± 1.07	0.09
5f: What is your general perception of the design process?	3.57 ± 1.27	4.00 ± 1.53	0.62

Discussion / Conclusions

This study explores students' perceptions of their capstone design experience. Our results suggest that our course restructure (i.e., framing the design process within the context of three pillars of operation) supports the development of a "post-academic" mindset, including strengthening student perception of the importance/relevance of design documentation and project-specific schedules. This work furthers the conversation begun by other researchers calling for curriculum development to be mapped not only to technical skills but also professional skills necessary for a successful engineering career [13], [14].

Interestingly, there was a significant shift in student perception of the relevance of the Risk Management Pillar, both to the senior design course and to their future careers. This finding suggests that students are gaining an understanding of the importance of planning for unanticipated problems. On average, students perceived "identifying mitigation plans" as the most relevant risk management skill to their future careers, but did not see it to be as relevant to the course. This finding suggests that students may still be relying on their instructors' influence for successful delivery of a prototype and completion of the course.

While changes in student perception of the relevance of the overall Project Management Pillar were not significant, there was a significant shift towards agreement with the relevance of specific project management skills to the course and future careers: building Gantt charts, making tasks assignments, and estimating activities need for the project. Interestingly, these skills all relate to time management, which contradicts the notion that students are continuing to rely on their instructors to successfully finish their projects and deliver a working product to their customers. Student perception of the relevancy of skills related to managing budgets and presenting project updates/design reviews did not change.

Although the changes in student perception of the relevance of the overall Design Control Pillar were not significant, there was a significant shift towards agreement with the relevance of specific skills to the course and future careers: writing design requirements, developing design requirements traceability, managing a design control spreadsheet, creating a concept of operations, using methods of estimate, and keeping a design notebook. At the time this survey was administered, many student teams had not yet started verification of their designs. It will be interesting to see if there is a significant shift in perceived relevance of system diagrams and verification methods as students carry out this phase of the design process.

One limitation of this study is our low response rate of ~35% (12/34 students). To address this limitation, we will collect end-of-course perception data from this year's students. We will also administer the survey to next year's senior design cohort, which is projected to have ~60 students. This year's small cohort is atypical for our institution and is likely the result of the impact of COVID (most students in our 2022-23 cohort were first years in AY 2019-2020).

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