How can we instill a post-academic mindset in capstone design?

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Introduction and Background

At the culmination of their undergraduate studies, engineering students participate in a capstone design experience that requires them to synthesize learned knowledge and apply developed skills to an open-ended design problem. Most capstone programs focus on project-based, hands-on learning that challenges student teams to identify customer requirements, translate customer requirements to design requirements, and ultimately develop solutions for a customer-provided problem. The open-ended nature of customer-provided problems is one of the main challenges students face during their capstone experience [1]. For most students, creating workable solutions to resolve the often unpredictable and conflicting nature of these types of problems proves to be vastly different from their previous undergraduate coursework [2]-[7]. Preparing students for successful entry into the workforce post-graduation is arguably one of the primary objectives of capstone design. Therefore, the aforementioned challenge is an intended one. To successfully prepare students for the workforce, instructors must help them shift from an "instructor-led learner" (i.e., academic mindset) to a "self-directed learner" (i.e., post-academic mindset) [8]. Some students embrace the unpredictable and quickly transform to self-directed learners, while others find the adjustment to be more difficult. Furthermore, instructor observations at our institution suggest that the capstone documentation requirements (reports, design notebooks, etc.), despite being a reality in any engineer's working career, further exacerbate the difficulties already associated with a change in mindset.

At our institution, we structure our 30-week capstone design program around a semi-imaginary consulting engineering firm, "Mountain Top Engineering," to help facilitate the transition from an academic to a post-academic mindset. The consulting firm's customers (industry and non-profit sponsors) provide design problems, and the CEOs (course instructors) assign multidisciplinary teams of associates (mechanical, electrical, and computer engineering students) to tackle these problems. From the onset of the course series, the firm operates on three established pillars of operation: Project Management, Risk Management and Design Control (Figure 1). *Project Management* focuses on developing a project-specific schedule, assigning individual tasks, and managing expenses within a project-specific budget. *Design Control* focuses on gathering customer requirements, developing design requirements, and creating and verifying design solutions. *Risk Management* focuses on identifying project and product risks, assessing the potential severity of those risks, and developing appropriate mitigation plans. More details regarding the implementation of these pillars can be found in the authors' earlier published work [9].

While industry sponsored capstone projects are not new [10, 11], we were interested to see if framing capstone design within the context of an engineering firm would promote student development of a truly post-academic mindset and a better appreciation for design documentation during the process.

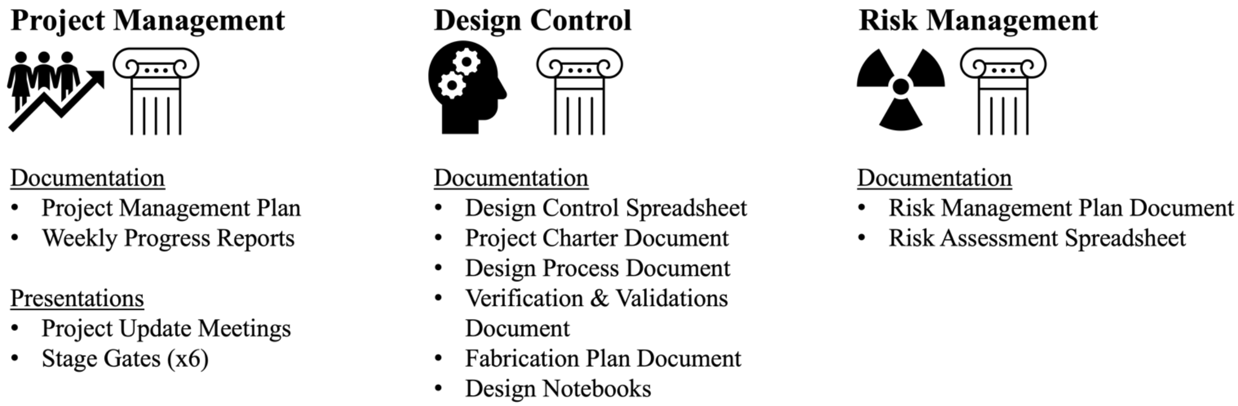

Figure 1: Three pillars of operation were scaffolded through the 30-week course series. The deliverables associated with each pillar were presented to students during the first week of class. Pillars were assigned a unique slide tag that was used in subsequent lecture materials to indicate the relevant pillar(s) of operation to the topic in discussion. Adapted from [9].

Prior to implementing the engineering firm framework, the capstone design documentation requirements consisted of seven deliverables: (1) *Requirements Document* including project scope and deliverables, design requirements, and preliminary verification plans); (2) *Project Management Plan* including organizational chart, risk assessment, project schedule and budget; (3) *Design Document* including design overview, system-level design, subsystem-level design, and impact of design; (4) *Verification Plan* including verification/validation procedures and results; (5) *Fabrication Plan* including piece part drawings, assembly drawings, detailed integration instructions and code, procured parts documentation, and software documentation; (6) *Progress Reports* including recent accomplishments, upcoming plans, current risks & mitigation plans, project timeline and budget status; and (7) *Design Notebooks*. First drafts of the *Requirements Document*, *Project Management Plan*, and *Design Document* were due during the Fall Quarter (Weeks 1-10 out of 30), first drafts of the *Verification* and *Fabrication Plans* were due during the Winter Quarter (Weeks 11-20 out of 30), and *Progress Reports* and *Design Notebooks* were due at regular intervals throughout the 30 weeks. The instructors who used this approach to documentation found it immensely challenging to convince students that documentation aids progress. Furthermore, the instructors observed a disconnect between student understandings of documentation and design work, perhaps due to students viewing the timeline for documentation deliverables as disjointed.

In contrast, the CEOs of "Mountain Top Engineering" presented the documentation deliverables as an integral part of the pillars of operation and the firm's ability to successfully operate from the onset. The pillars were intentionally discussed with students during the first week of classes in hopes of demonstrating that documentation is a tool for, not a hinderance to, success. The course restructure included the following updates to documentation: (1) The *Requirements Document* was replaced by a *Project Charter*, which captured customer requirements (new) and design requirements; (2) A *Design Control Spreadsheet* was introduced to: (i) map customer requirements to design inputs; (ii) map design inputs to design outputs & verification (outputs = features/elements/solutions meeting the design inputs; verification = methods and procedures, including references to relevant documents and/or protocols, that confirm verification of design outputs to design inputs); (iii) map customer requirements to design validation (methods and procedures, including relevant references to reports and/or work, that confirm validation of outputs to customer requirements); (iv) qualitatively assess design concepts by mapping design inputs to an importance scale via a Pugh matrix; (3) A *Risk Assessment Spreadsheet* was introduced to track descriptions of risks, risk scores, mitigation plans, and mitigated risk scores, when applicable; and (4) The *Project Charter*, *Design In-Process Document* (previously referred to as the *Design Document*), *Verification Plan* and *Fabrication Plan* were not introduced as stand-alone documents, but rather as chapters within a single report that associates continuously populated throughout the year. The *Project Management* and *Risk Management Documents* were retained from the "old approach" and captured the project planning and risk management aspects of the project as the design work progressed.

The purpose of this study, which builds upon some of the authors' previous work [9], was to determine if the associates (our students) became more confident in their abilities to apply their skills and solve open-ended problems with multiple potential solutions. More specifically, we aimed to address the following research questions: As students progress through their capstone experience, do they…

(1) increasingly perceive senior design more so as a project experience than a course for credit?
(2) increasingly perceive the 3 pillars of operation as useful/relevant to the capstone course?
(3) increasingly perceive the 3 pillars of operation as useful/relevant to their future career?
(4) feel increasingly confident that senior design will prepare them for their future career?
(5) have an increasingly positive perception of the design process and project deliverables (e.g., design documentation)?

We hypothesized that students would: (1) increasingly perceive senior design more so as a project experience than a course for credit, (2) increasingly perceive the 3 pillars of operation as useful/relevant to the capstone course, (3) increasingly perceive the 3 pillars of operation as useful/relevant to their future careers, (4) feel increasingly confident that senior design will prepare them for their future careers; and (5) have an increasingly positive perception of the design process and project deliverables.

Methods

This study was carried out under IRB approval. The course instructors invited all the capstone students to complete a voluntary, anonymous, online Qualtrics survey via an online learning management system announcement. The survey was designed to take 5-10 minutes to complete and was administered twice, once at the beginning and once at the end of the 30-week course series. Students who agreed to participate (n=41) were prompted (not forced) to answer 19 survey questions. A 5-point Likert assessment scale was used for all but one question, which was assessed on a 7-point Likert assessment scale. Data from the second cohort that was taught using the engineering firm framework is presented here. Pilot data collected from first cohort was presented in a previous work-in-progress paper [9], but data from the two cohorts were not combined due to confounding factors.

Differences between pre-course and current-course student perceptions were evaluated with a paired two-sample t-test. Significance levels were adjusted using a Bonferroni correction to account for Type I errors. Adjusted significance levels, α_{adj}, where calculated for each hypothesis by dividing 0.05 by the number of statistical tests applicable to the hypothesis in question.

Results

Perceptions of senior design as a project experience vs. course for credit ($\alpha_{adj} = 0.0125$): Results indicate a significant shift in student perception towards: (i) viewing senior design more so as a project experience than a required course for graduation ($p < 0.001$; Table 1, Survey Question 1a); and (ii) seeing themselves as associates of our semi-imaginary firm ($p < 0.001$; Table 1, Survey Question 1d). After accounting for the Bonferroni adjustments, we saw no significant differences in student level of agreement with the notion that following the course curriculum and completing instructor-provided assignments would result in successful delivery of their projects ($p = 0.0176$; Table 1, Survey Question 1b). Similarly, we found no significant differences in student level of agreement with the notion that following these same steps would result in their receiving of a good grade ($p = 0.1829$; Survey Question 1c). Students indicated overall agreement with the statement "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" in both pre-course and current perceptions (mean ± std: 4.51 ± 0.64 and 4.37 ± 0.83 on a 5-point Likert agreement scale, respectively).

Table 1: Survey data reflecting student pre-course and current perceptions of the senior design experience. Differences were considered significant for $\alpha_{adj} = 0.0125$. [a] indicates assessment on a 7-point Likert agreement scale (1 = entirely a course for graduation, 4 = equally a course for graduation and a project experience, 7 = entirely a project experience); [b] indicates assessment on a 5-point Likert agreement scale (1 = strongly disagree, 3 = neither agree nor disagree, 5 = strongly agree); ** indicates significant differences for $p < 0.001$; # indicates a shift in response past neutral.

Survey Question	**Perception (mean ± std dev)**	
	Pre-Course	**Current**
1a: Do you think of Senior Design primarily as a course you need for graduation or as a project experience? [a,**,#] (n=41)	3.76 ± 1.87	4.80 ± 1.47
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. [b] (n=41)	4.20 ± 0.71	3.78 ± 1.08
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. [b] (n=41)	4.51 ± 0.64	4.37 ± 0.83
1d: I see myself as an associate of Mountain Top Engineering - Class of 2023 LLC. [b,**] (n=39)	3.38 ± 1.07	4.46 ± 1.00

Perceptions of the 3 pillars of operation as useful/relevant to the capstone course and/or future career ($\alpha_{adj} = 0.00106$): On average, students were slightly familiar with the three pillars of operation at the onset of the course (pre-course perceptions) but reported being moderately to very familiar by the end (current perceptions) (Table 2). These changes were found to be significant for all three pillars of operation ($p < 0.001$). Additionally, student perception of the usefulness/relevance of the pillars to both the capstone design course and their future careers significantly increased over the 30-weeks ($p < 0.001$) (Tables 3 and 4). This significant increase extended to the usefulness of the skills associated with each pillar ($p < 0.001$).

Student confidence that senior design will prepare them for their future careers ($\alpha_{adj} = 0.025$): Results also indicated significant increases in student self-confidence in their preparedness for their future careers and their ability to complete project deliverables without instructor defined assignments ($p < 0.01$; Table 5, Survey Questions 5a and 5b).

Student perception of the design process and project deliverables ($\alpha_{adj} = 0.0125$): Students indicated a significant increase in their level of agreement with the design process being "fun" and "positive" ($p < 0.01$; Table 5, Survey Questions 5c and 5f). This increasingly positive perception of the design process was accompanied by a significant increase in student agreement with the ideas that documentation is integrally important to the design process and that course deliverables are important to the successful completion of their project ($p < 0.01$; Table 5, Survey Questions 5d and 5e).

Table 2: Student self-reported familiarity with the three pillars of operation on a 5-point Likert agreement scale (1 = not at all familiar, 3 = moderately familiar, 5 = extremely familiar agree). Differences between pre-course and current course perceptions were significant for all three pillars ($\alpha_{adj} = 0.00106$, $p < 0.001$). n-value indicates the number of student responses.

Survey Question	**Perception (mean ± std dev)**	
	Pre-Course	**Current**
2a: What is your familiarity with the following pillars of operation? (n=41)		
Project Management Pillar	2.07 ± 0.93	3.95 ± 0.83
Design Control Pillar	1.95 ± 0.86	3.85 ± 0.76
Risk Management Pillar	1.80 ± 0.87	3.73 ± 0.74

Table 3: Student self-reported perception of the usefulness/relevancy of the 3 pillars of operation to the capstone course assessed on a 5-point Likert scale (1 = not at all useful/relevant, 3 = moderately useful/relevant, 5 = extremely useful/relevant). Differences between pre-course and current perception were found to be significant for $p < 0.001$ for all survey questions (α_{adj} = 0.00106). # indicates a shift from less than moderately useful/relevant to more than moderately useful/relevant (i.e., from an average response of <3 to an average response of >3). n-values indicate the number of student responses.

Survey Question	Perception (mean ± std dev)	
	Pre-Course	Current
3a: Are the following pillars of operation relevant to the senior design course? (n=40)		
# Project Management Pillar	2.88 ± 0.85	4.03 ± 0.80
Design Control Pillar	3.10 ± 0.90	4.05 ± 0.75
# Risk Management Pillar	2.88 ± 0.94	3.95 ± 0.81
3b: Are the following (project management) skills relevant to the senior design course? (n=39)		
# building Gantt Charts	2.59 ± 0.97	3.49 ± 1.10
making task assignments	3.15 ± 0.93	4.26 ± 0.85
estimating activities needed for a project	3.18 ± 1.00	4.28 ± 0.60
estimating project costs	3.36 ± 1.18	4.15 ± 0.84
preparing written project updates	3.21 ± 0.95	4.21 ± 0.73
preparing and presenting project updates	3.51 ± 0.91	4.31 ± 0.66
presenting Stage Gate reviews	3.28 ± 1.02	4.33 ± 0.70
3c: Are the following (design control) skills relevant to the senior design course? (n=38)		
writing design requirements	3.50 ± 1.03	4.50 ± 0.65
# keeping a design requirements traceability matrix	2.84 ± 1.10	3.82 ± 0.80
managing a design control spreadsheet	3.05 ± 1.01	3.79 ± 1.02
creating a concept of operations	3.16 ± 1.00	4.05 ± 0.93
drawing a systems diagram	3.29 ± 0.96	4.21 ± 0.87
defining a functional decomposition	3.08 ± 0.88	4.03 ± 0.79
defining a method of verification	3.26 ± 0.92	4.39 ± 0.64
using methods of estimation	3.03 ± 0.94	3.95 ± 0.96
# keeping a design notebook	2.76 ± 1.00	3.92 ± 1.10
3d: Are the following (risk management) skills relevant to the senior design course? (n=38)		
# making a risk management plan	2.92 ± 0.75	4.05 ± 0.69
# using a risk assessment spreadsheet	2.66 ± 0.97	3.87 ± 0.96
identifying mitigation plans	3.13 ± 0.93	4.29 ± 0.80

Table 4: Student self-reported perception of the usefulness/relevancy of the 3 pillars of operation to their future careers assessed on a 5-point Likert scale (1 = not at all useful/relevant, 3 = moderately useful/relevant, 5 = extremely useful/relevant). Differences between pre-course and current perception were found to be significant for $p < 0.001$ for all survey questions (α_{adj} = 0.00106). # indicates a shift from less than moderately useful/relevant to more than moderately useful/relevant (i.e., from an average response of <3 to an average response of >3). n-values indicate the number of student responses.

Survey Question	Perception (mean ± std dev)	
	Pre-Course	**Current**
4a: Are the following pillars of operation relevant to your future career? (n=41)		
Project Management Pillar	3.14 ± 0.99	4.07 ± 0.88
Design Control Pillar	3.10 ± 1.02	3.89 ± 1.03
# Risk Management Pillar	2.95 ± 1.00	4.00 ± 0.92
4b: Are the following (project management) skills relevant to your future career? (n=41)		
# building Gantt charts	2.12 ± 0.81	3.22 ± 0.96
making task assignments	3.62 ± 1.02	4.39 ± 0.63
estimating activities needed for a project	3.39 ± 1.04	4.41 ± 0.59
estimating project costs	3.61 ± 1.11	4.22 ± 0.88
preparing written project updates	3.07 ± 0.93	3.98 ± 0.88
preparing and presenting project updates	3.54 ± 0.90	4.32 ± 0.72
presenting stage gate reviews	3.07 ± 1.03	3.93 ± 0.93
4c: Are the following (design control) skills relevant to your future career? (n=40)		
writing design requirements	3.50 ± 0.99	4.55 ± 0.68
# keeping a design requirements traceability matrix	2.80 ± 0.99	3.78 ± 0.97
# managing a design control spreadsheet	2.70 ± 0.97	3.65 ± 1.12
# creating a concept of operations	2.90 ± 1.06	4.08 ± 1.07
drawing a systems diagram	3.32 ± 0.97	4.05 ± 0.99
defining a functional decomposition	3.10 ± 0.93	3.85 ± 1.03
defining a method of verification	3.27 ± 0.96	4.33 ± 0.86
using methods of estimation	3.02 ± 0.95	3.90 ± 0.90
# keeping a design notebook	2.45 ± 1.13	3.63 ± 1.12
4d: Are the following (risk management) skills relevant to your future career? (n=40)		
# making a risk management plan	2.85 ± 0.86	4.08 ± 0.66
# using a risk assessment spreadsheet	2.55 ± 0.84	3.53 ± 0.96
identifying mitigation plans	3.07 ± 0.94	4.2 ± 0.72

Table 5: Survey data to assess: (i) students' level of confidence that senior design will prepare them for their future career; and (ii) students' overall perceptions of the design process and project deliverables. Differences between pre-course and current perceptions were considered significant for $\alpha_{adj} = 0.025$ (Survey Questions 5a, 5b) and $\alpha_{adj} = 0.0125$ (Survey Questions 5c-5f). Responses were captured on a 5-point Likert scale ([a] indicates 1 = strongly disagree, 3 = neither agree nor disagree, 5 = strongly agree; [b] indicates 1 = extremely negative, 3 = neither positive nor negative, 5 = extremely positive). [*] indicates $p < 0.01$; [**] indicates $p < 0.001$. n-value indicates the number of student responses.

Survey Question (n=39)	**Perception (mean ± std dev)**	
	Pre-Course	**Current**
5a: I am confident that senior design prepares me for my future career as an engineer. [a,*]	3.92 ± 0.70	4.54 ± 0.68
5b: I am confident that I could deliver my project without instructor defined deliverables. [a,*]	3.08 ± 1.16	3.67 ± 1.13
5c: I think the design process is fun. [a,*]	4.03 ± 0.78	4.44 ± 0.60
5d: The course deliverables are important to the successful completion of my project. [a,**]	3.74 ± 0.91	4.23 ± 0.78
5e: Documentation is integrally important to the design process. [a,*]	3.62 ± 1.07	4.46 ± 0.68
5f: What is your general perception of the design process? [b,*]	3.95 ± 0.72	4.46 ± 0.64

Discussion / Conclusions

This study investigates student perceptions of capstone design and whether these perceptions change from the beginning to end of their experience. The results presented here support the idea that our course structure (i.e., framing the design process and documentation requirements within the context of three pillars of operation) may foster a positive change in student mindset.

On average, students initially perceived senior design to be more so a course for graduation than a valuable project experience. However, at the end of 30-weeks students indicated they perceived senior design to be more so a project experience than a course for graduation. Furthermore, students indicated a decreasing level of agreement with their ability to successfully deliver their project to the customer by following the course curriculum and instructor provided assignments. In combination, these findings suggest a shift in student mindset towards self-directed learning and an overall positive change in their attitude and perception of the primary goal of the capstone experience. Results also indicated significant increases in students' self-confidence in their preparedness for their future careers and their ability to complete project deliverables without instructor defined assignments. This result indicates that students felt less dependent on their course instructors at the end of the 30-weeks, further suggesting a shift towards self-directed learning.

Students initially perceived the relevance of the project management and risk management pillars to be less than moderately relevant to the capstone course, but as very relevant by the end of their 30-week experience. Looking at the skills associated with each of the three pillars, the same trend (i.e., a shift from less than to more than moderately useful/relevant) was observed in one project management skill (building Gantt Charts), two design control skills (keeping a design traceability matrix, keeping a design notebook), and two risk management pillar skills (making a risk management plan, using a risk assessment spreadsheet). These results suggest that students perceived an increased usefulness/relevancy of skills related to planning, organizing, and preparing for the unpredictability of long-term, large-scope projects. Similarly, students indicated a change in their perception of the usefulness/relevancy of the risk management pillar to their future career from less than to more than moderately relevant, as well as building Gantt Charts, keeping a design traceability matrix, keeping a design notebook, making a risk management plan and using a risk assessment spreadsheet. Managing a design control spreadsheet and creating a concept of operations also showed this same trend.

The trends demonstrated by the data in Tables 3 and 4 support the need for us to teach our students both the technical and professional skills necessary for their post-graduation success [12], [13]. This approach includes teaching students of the importance of project documentation. Based on our experiences with teaching previous student cohorts, we were concerned about student perception of documentation and its role in the design process. The results presented here indicate that students overwhelmingly grew more favorably towards documentation and the understanding of its importance. This shift was accompanied by increased agreement with the design process being fun, increased feelings of preparedness to enter the engineering workforce, and an increasingly positive perception of the design process (Table 5).

Instructors of capstone design are continuously looking for ways to improve their courses. The results of this study suggest that mimicking a firm structure could foster an environment conducive to increasingly positive student attitudes and perceptions of the design process, including both project and risk management. Future work should include additional data from additional student cohorts to determine whether there is a direct cause and effect or a correlation between the two.

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