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STUDENT PAPER: What We Learned, When We Learned It, and How We Learned It: Takeaways from an Institution's Aerospace Engineering Capstone Experience

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What We Learned, When We Learned It, and How We Learned It: Takeaways from Saint Louis University's Aerospace Engineering Capstone Experience

Abstract

Aerospace engineering requires a broad foundation of skills students are to develop throughout their educational careers. Beyond the physics and mathematics fundamentals, it can be beneficial for students to explore more specialized topics or platforms that interest them. For some students at Saint Louis University, this specialization can appear as late as their final capstone projects where they are to design (and in some cases, build) a system such as an aircraft, rocket, or spacecraft. This paper offers a reflection from alumni of an aerospace engineering undergraduate program on the impacts of the required course track (fundamentals) for their degree on the success of their final capstone projects (specialization). Within some engineering programs, a disconnect can occur when the specialized interests of the student do not align well with the required or offered course material. This paper identifies some areas where students had gaps in their knowledge and experiences, as well as what they had to do to fill in those gaps. The methods used to gather the reflections included a survey of alumni as well as expanded case studies provided by the authors. The findings suggest that required course-tracks are lacking hands-on engineering experiences such as learning about manufacturing or the use of specialized software programs. Further, some course-tracks focus on particular topics in aerospace engineering and students interested in other areas are left to fill their knowledge gaps on their own. Though the primary course-tracks for engineering programs may be lacking in structured routes for specialization, capstone projects are seen to provide students with the opportunity to augment coursework knowledge with specialized skills and to explore different aspects of the design process before graduating. The findings suggest this is done by applying skills learned from extracurriculars or internship experience. In addition, input from mentors—either those who work in industry or professors—can also prove to be a valuable asset. The capstone also affords students the opportunity to cooperate and communicate with other engineers—another aspect of engineering not taught explicitly—to achieve more successful results.

Introduction and Background

Senior Design and Specialization

Senior Design is an integral part of the engineering education experience at the undergraduate level, and it is required for a program to be accredited by the Accreditation Board for Engineering and Technology (ABET). In terms of curriculum, ABET-accredited programs must include at least 30 credit hours of college-level mathematics and basic sciences, at least 45 credit hours of engineering topics appropriate to the particular program, a component of broader education that complements the technical content and is consistent with the program's educational objectives, and a culminating major engineering design experience that incorporates engineering standards and constraints and is based on the knowledge and skills acquired from previous courses [1]. For aerospace engineering programs, the “major design experience,” commonly referred to as Senior Design or a Senior Capstone project, must include topics relevant to the program. Senior design serves as a “training ground” or “sandbox” for students to overcome the challenges they might encounter in their career but with guidance from instructors. The skills and knowledge applied in Senior Design require a comprehensive understanding of subject material from multiple courses over previous years. Senior Design can simulate real-life experience and can provide helpful skills for students to take to their work environment after they graduate. From another perspective, students will have an opportunity to expand their limited (classroom) understanding of engineering design, further filling the gap between what an engineering student and a practicing engineer will emphasize in their career [2].

This research on specialization was inspired by the experiences of the authors during their Senior Design at Saint Louis University (SLU). Specialization is considered here to be the narrowed area of expertise of an engineer beyond their chosen engineering discipline. For example, aerospace engineering is considered to be the chosen engineering discipline while a student can choose to further specialize in spacecraft design. Alternatively, a student may not wish to choose a vehicle type to specialize in, but an area of theory such as solid mechanics or control systems. Furthermore, a student may also not choose a specialization, but nonetheless be required to acquire knowledge and skills in specialized areas for projects, academic or ones in industry.

The purpose of this exploratory study is to offer a reflection and discussion on the impacts of the required course track—the engineering fundamentals—on the Senior Design experience, or specialization. The qualitative analysis conducted identifies areas where students had gaps in their knowledge and experiences during Senior Design and what they had to do to fill in those gaps “on the fly.” It also identifies where or how students learned skills outside of the required course track prior to or during their Senior Design course that aided in their experience.

Literature Review

In a study conducted at Georgia Tech, it was found that struggles in foundation-level classes for mechanical engineering students may be a predictor to lower GPA, longer degree completion time, or transfer out of the mechanical engineering major [3]. Given the similarities between most aerospace and mechanical engineering programs, this finding could be extrapolated to aerospace engineering students. This finding serves to emphasize the importance of fundamental engineering courses on overall student success.

Another research publication [4] indicates the disconnect between engineering education and the implementation of engineering solutions proposed in Senior Design projects. It was found that the industrial engineering student projects studied attempt to solve problems from an academic perspective, a perspective which lacks the crucial, “authentic” factors that any real-world engineering solution should have. Students hold greater emphasis on the use of the industrial engineering tools demonstrated in class, and their design plans follow the processes described in their coursework despite the "limited breadth" in which the problem space is explored using those tools. The result of this study emphasizes the disconnect between the intended goal of Senior Design as a demonstration of a student's ability to solve realistic problems and how students apply their academic knowledge to these realistic problems.

In another study [2] of mechanical engineering students, the relationship between particular course categories taken prior to Senior Design and the skills students perceived as important were found. The results of this study demonstrated that at the institution studied, the students perceived their "engineering core" (mechanics and materials, beyond general science and math), "engineering design" (courses focused on design), and "engineering track core" (concentration) courses as important during their Senior Design experience. Further, the study also evaluated the students' perceived confidence in the skills considered important, demonstrating what could be considered influential components of the curriculum. Though these skills could be identified, there were few relationships to note between courses and the skills, perhaps indicating "that the courses are not directly impacting these skills, are negatively impacting these skills, or are not emphasizing the skills within the courses." These findings serve to emphasize the importance of specialization experiences—in engineering core / design and more specifically in a student's concentration area—prior to the Senior Design experience.

Background of SLU's program of study

At SLU—and prior to the implementation of a new University Core Curriculum—aerospace engineering students were required to take 127 credits to graduate, or about 42 classes. The curriculum plan from the year 2017 is provided in Figure 1 below for reference. Just 6 of those classes allow for student choice, and three of those six must be in a non-engineering department. This means an aerospace engineering student has only 2-3 courses in which they can specialize in an area of their interest, assuming a course in the area of interest to the student is offered in the semester(s) they take their electives.

It is worth noting that the maximum number of credits a student can take without "overloading" is 18, so the maximum number of courses a student could take is about 48, allowing potential for more specialized coursework. Further, some students come into the institution with credits that can be applied to some required classes or electives, resulting in more potential for specialized coursework. It may be worth quantifying in future research how many credits aerospace engineering students take in actuality, not just what is laid out in the curriculum plan.

SAINT LOUIS UNIVERSITY
PARKS COLLEGE OF ENGINEERING, AVIATION & TECHNOLOGY
2017 - 2018 AEROSPACE ENGINEERING CURRICULUM PLAN

Last Name____________________________ First Name________________________ Banner ID______________________

COURSES IN BOLD WILL BE OFFERED ONLY ONCE A YEA R

FRESHMEN YEAR

FALL		SPRING	
☐ AENG 1001 INTRO TO AE/ME	1__	☐ AENG 1002 COMPUTER AIDED ENGINEERING DESIGN	1___
☐ CHEM 1110/1115 (1070/1075) GEN CHEMISTRY I / LAB	4__	☐ CSCI 1060 SCIENTIFIC PROGRAMMING (pcr-MATH 1510)	3___
☐ ENGL 1920 ADV. WRITING FOR PROF.	3__	☐ MATH 1520 CALCULUS II (p-MATH 1510) **	4___
☐ MATH 1510 CALCULUS I *	4__	☐ PHYS 1610 ENG. PHYSICS I (p-MATH 1510)	3__
☐ THEO 1000 THEOLOGICAL FOUNDATIONS	3__	☐ PHYS 1620 ENG. PHYSICS I LAB (c-PHYS 1610)	1__
		☐ HUMANISTIC VALUES ELECTIVE$	3__
	15		**15**

SOPHOMORE YEAR

FALL		SPRING	
☐ **AENG 2000 INTRO TO AERO & ASTRO** (pcr-AENG 1002, pcr-PHYS 1610)	**3__**	☐ ESCI 2100 STATICS (pcr-PHYS 1610)	3__
☐ MENG 2011 ENG. SHOP PRACTICE	1 __	☐ ESCI 2150 DYNAMICS (pcr-ESCI 2100, p-MATH 1520)	3__
☐ MATH 2530 CALCULUS III (p-MATH 1520)	4__	☐ ESCI 2300 THERMODYNAMICS (pcr-MATH 2530)	3__
☐ PHYS 1630 ENG. PHYSICS II (p-MATH 1520,p-PHYS 1610)	3__	☐ ESCI 3200 FLUID DYNAMICS (pcr- MATH 2530)	3__
☐ PHYS 1640 ENG. PHYSICS II LAB (c-PHYS 1630)	1__	☐ ESCI 3201 FLUID DYNAMICS LAB (c-ESCI 3200)	1__
☐ HUMANISTIC VALUES ELECTIVE$	3__	☐ MATH 3550 DIFF. EQUATIONS (p-MATH 2530)	3__
	15		**16**

JUNIOR YEAR

FALL		SPRING	
☐ **AENG 3000 PERFORMANCE (p-AENG 2000)**	**3__**	☐ AENG 3100 COMPUTER AIDED ENGG (p-CSCI 1060, p-ESCI 3100,)	3__
☐ ECE 2001 ELECTRICAL ENG'G (p-MATH 1520, p-PHYS 1610)	3__	☐ **AENG 3150 ASTRODYNAMICS (p-AENG 2000, p-ESCI 2150)**	**3__**
☐ ECE 2002 ELECTRICAL ENG'G LAB (c-ECE 2001)	1__	☐ **AENG 3210 GAS DYNAMICS (p-ESCI 2300, p- ESCI 3200, pcr- MATH 3270)**	**3__**
☐ ESCI 3100 MECH OF SOLIDS (p-ESCI 2100, pcr-MATH 2530)	3__	☐ **AENG 3220 AERODYNAMICS (p-ESCI 3200, pcr- MATH 3270)**	**3__**
☐ ESCI 3101 MECH OF SOLIDS LAB (c-ESCI 3100)	1__	☐ ESCI 3410 LINEAR SYSTEMS (p-ESCI 3110)	3__
☐ ESCI 3110 LINEAR VIBS (p-ESCI 2150, p-MATH 3550)	3__	☐ MATH /SCIENCE ELECTIVE %	3__
☐ MATH 3270 ADV. MATH FOR ENGINEERS (pcr-MATH 3550)	3__		
	17		**18**

SENIOR YEAR

FALL		SPRING	
☐ **AENG 4004 DESIGN I/Lab (p-AENG 3000, pcr AENG 4400)**	**3__**	☐ **AENG 4014 DESIGN II/Lab (p-AENG 4004)**	**3__**
☐ **AENG 4110 FLIGHT VEHICLE STRUC (pcr-AENG 3100)**	**3__**	☐ PHIL 3400 ENGINEERING ETHICS	3__
☐ **AENG 4111 AEROSPACE LAB (p-AENG 3000, pcr- AENG 4110)**	**1__**	☐ CULTURAL DIVERSITY ELECTIVE ##	3__
☐ **AENG 4210 PROPULSION (p-AENG 3210)**	**3__**	☐ TECH ELECTIVE %	3
☐ **AENG 4400 STABILITY & CONTROL (p-AENG 3000, pcr- ESCI 3410)**	**3__**	☐ TECH ELECTIVE %	3__
☐ MENG 4300 HEAT TRANSFER (p-CSCI 1060, p- ESCI 2300, p-ESCI 3200)	3__		
	16		**15**

TOTAL 127

p = pre-requisite; must be taken before	$ humanistic values elective shall be chosen from Philosophy, Theology, Social and Behavioral sciences, or humanities
c = co-requisite; must be taken at the same time	% Select from an approved list of courses
pcr = pre-co-requisite; can be taken before or at the same time	## Replace with Hum-Values elective for students with international origin or experience (study abroad)
* requires proficiency exam; must earn a grade of C- or above	
** must earn a grade of C- or above	

Figure 1. SLU Aerospace Engineering Curriculum Plan, 2017 [5]

Background of SLU's Senior Design Process

At SLU, the engineering Senior Design experience takes place across a full academic year, with students taking Design I in the fall semester and Design II in the spring. Some of the learning objectives for Senior Design include innovation, engineering design, engineering analysis, communication skills, problem solving skills, entrepreneurial skills, organizational skills, budgetary skills, planning skills, and teamwork while going through a project the way that it would be done in industry. Senior Design is also meant to provide students with an opportunity to demonstrate what they have learned in their previous courses and expose students to an environment similar to what they may experience in the workplace.

As part of the aerospace engineering Senior Design program, teams of 4-6 students are given a $500 budget to complete projects of their choosing in vehicle design. These tend to fall under one of three categories: aircraft, rocket, or spacecraft. Of the three, the most common project is an aircraft project. The reason for this is hypothesized as being due to the limited number of spacecraft-related courses offered because the background and history of SLU's aerospace program is in aircraft. These projects often include designing and building an aircraft with the intention of completing flight testing during the Design II course, and these teams also sometimes compete in aircraft design competitions. Groups that opt to design a rocket also tend build at least a portion of their design leaving the spacecraft projects as an outlier given they (often) cannot be designed and built in the time or budget allotted.

The course catalog describes Design I as "an application of aerospace engineering to the design methodology of a flight vehicle." The Design I course meets for a scheduled 6 hours per week over 2 days with class time spent several ways. At the beginning of the semester (and at times throughout), there are professor-taught lectures to help students with aspects of the initial stages of their projects such as defining requirements and conducting trade studies. There are, on occasion, guest lectures on topics such as business strategies and career development. Mid-way through the semester, class time shifts to project team working sessions, and meetings with the instructors to track progress and ask questions.

The goal of Design I is to get teams to the point in their project such that a presentation and report at the end of the semester is similar to an industry preliminary design review (PDR). By the end of the first semester, teams are expected to have all the following items:

- An overview of the reasons for the design
- A clear set of requirements, including technical, non-technical, system, and key subsystem requirements
- A first-order analysis showing that the design can reasonably meet the requirements
- A value proposition identifying advantages of the design
- An assessment of risks, both technical and non-technical
- A clear team organization and plan for project completion

- And, for projects that consist of a build portion, plans for construction and financing of the project.

The first semester culminates in a design review with industry professionals acting as reviewers and giving feedback on each project.

The course catalog description of Design II is "an application of aerospace engineering to the detail design of a flight vehicle, model design, fabrication testing, evaluation, and analysis." Design II begins with the assumption that each project has at least a preliminary design because the focus in this course is on completing the projects started in Design I. There are no longer traditional class lectures as class time is dedicated to making progress on the projects and checking in with the instructors. For groups that opt to build their project, Design II is where the majority of the manufacturing, integration, and testing takes place. Design II is different for groups who design vehicles outside the schedule and cost constraints of the academic course, most often the spacecraft teams. In lieu of building, these teams tend to focus on detailing their design, running simulations, or developing prototypes where possible. Similar to Design I, the semester concludes with a final presentation of design for industry professionals.

Methodology

To study the effect of the required course track (fundamentals) on the success of a student's capstone project (specialization), a survey was conducted of alumni of SLU's aerospace engineering undergraduate program. The survey questions were input into the Google Forms survey platform and distributed by the authors to alumni. The survey questions can be seen in Table 2 in the Appendix in addition to the type of response permitted. These questions focused on evaluating the perceived helpfulness of academic coursework, extracurricular design / build teams, and internship experiences to Senior Design, as well as the students' perceived preparedness and the perceived success of the course.

In addition to the collection of condensed survey responses, two case studies are presented as an in-depth, qualitative assessment of the Senior Design course at the institution discussed. The first case study looks at an aircraft design and build project from the class of 2021 that participated in the Association for Unmanned Vehicle Systems International Student Unmanned Aerial Systems (AUVSI SUAS) competition and built upon previous iterations of the competition aircraft. The second case study is of a spacecraft design feasibility study also completed in 2021.

Results

Survey Results

Because the survey only received 18 responses, comprehensive conclusions are not drawn. However, due to the exploratory nature of this work, some results are included here nonetheless as they provide valuable insights which corroborate the theme of the research, provide context to the expanded case-studies discussed later in this paper, and demonstrate the need for increased data collection in future work.

Question 1 of the survey asked respondents which courses leading up to Senior Design they believe best prepared them for the class; Table 1 below shows the results. It should be noted that of the 18 respondents, 9 completed spacecraft projects, 7 aircraft projects, and 2 rocket projects.

Table 1. Survey Results: Question 1

Course Name	Number of Mentions	Required or Elective?
Astrodynamics	9	Required
Space Mission Analysis and Design	5	Elective
Aerodynamics	4	Required
Aircraft Performance	4	Required
Fluid Dynamics	3	Required
Aircraft Vehicle Structures	2	Required
Computer-Aided Design	2	Required
Gas Dynamics	2	Required
Machine Shop	2	Required
Mechanics of Solids	2	Required
Scientific Programming	2	Required
Space Mission Integration and Test	2	Elective
Stability and Control	2	Required
Advanced Writing for Professionals	1	Required
Aerospace Laboratory	1	Required
Calculus	1	Required
Computer-Aided Engineering	1	Required
Differential Equations	1	Required
Introduction to Electrical Engineering	1	Required
Space Mission Failures	1	Elective
Thermodynamics	1	Required

In questions 2 and 3 of the survey, respondents were asked to rate on a scale of 1-10 (1 low, 10 high) how helpful their required and elective courses were to their Senior Design experience; Figures 2 and 3 show the results. The average score for the required courses was 6.67 and the average score for the elective courses was 7.33.

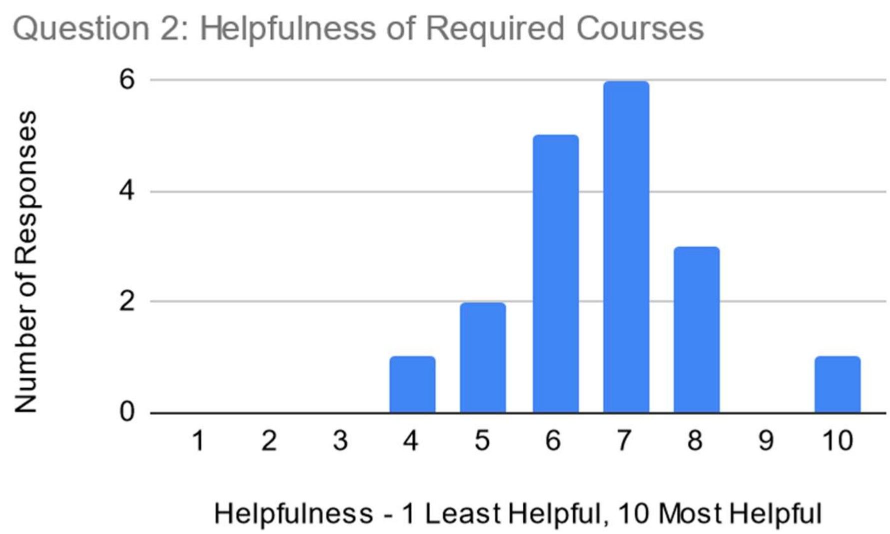

Figure 2. Student Ratings of Helpfulness of Required Courses

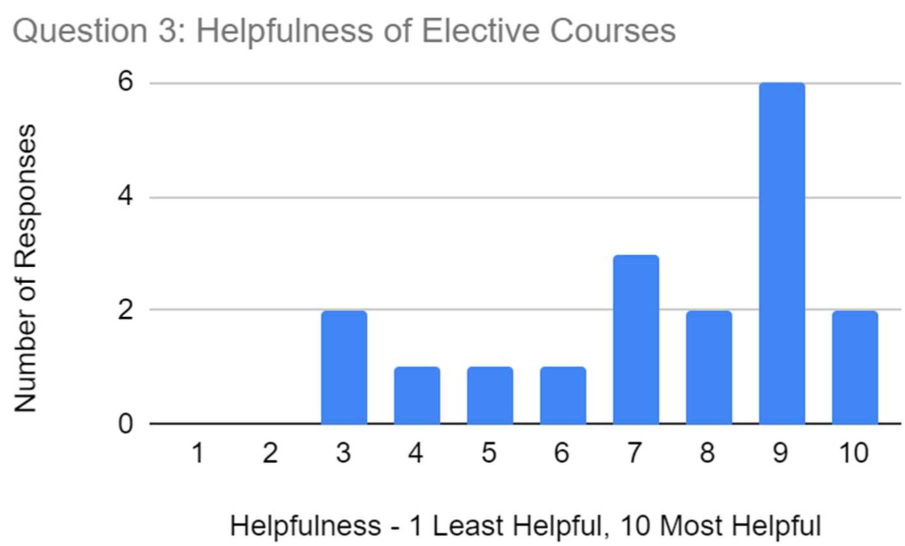

Figure 3. Student Ratings of Helpfulness of Elective Courses

Regarding coursework, some selected comments from survey respondents are shown below:

- *The actual engineering skills required to excel in senior design aren't exactly an integral part of any of these classes though. They teach the science of what you need to know, but the problem solving and critical thinking you'll inevitably use come from more of a person setting, rather than a class.*
- *The courses I took prior to / concurrent with Senior Design were important mainly for introducing me to problem solving techniques and engineering practices, not necessarily information directly related to my project.*

- *The courses provided useful skills and tools, which could then be applied to the project. But only a small (though necessary) portion of the project consisted of performing the analyses we learned in our courses.*
- *Working with people, seeing the different roles / responsibilities, and putting in the time to do what's necessary are some of the most important things you don't learn in the core classes.*

Of the 18 survey respondents, 16 participated in a design and build team prior to or during Senior Design. Though two of those respondents said they had participated but not applied skills from that experience to Senior Design, all 16 participants scored the helpfulness of their design and build experiences with a 5 or higher, with 15 of the 16 scoring their experience with an 8 or higher (out of 10). Of the options provided—required courses, electives, design and build team, and internship experience—respondents rated participation in a design and build team as the primary experience that prepared them for Senior Design. Regarding design and build experiences, some selected comments from survey respondents are shown below:

- *I think most of my practical knowledge, schedule development and execution came from the Design, Build, Fly team that I participated in as an extracurricular.*
- *My experience in design & build teams was useful for introducing me to working in teams, meeting deadlines, and solving problems in the 'real world.'*
- *Most of my design experience came from an extracurricular club that focused on the Design, Build, Fly competition. Out of 8 people focused on Speedfest, it was a huge leg up for our team to have my extracurricular experience building RC aircraft.*

12 of the 18 respondents participated in internships prior to Senior Design and rated the helpfulness of their internship experiences with an average score of 6.67 on a scale of 1 to 10. It is interesting to note that many of the comments about internships related to requirements development, program management, and soft skills rather than technical skills. Selected comments from survey respondents are shown below regarding internship experience:

- *Having been able to closely interact with and see the requirement development process made the first semester really straight forward since I knew what the expected outcome should be. Would not have known that without an internship.*
- *Internship provided a lot of industrial experience, including general project management and commitments to deadlines. This was the most useful tool to the team during Senior Design.*
- *My other internship was useful in learning how to approach program management. I learned Agile Methodologies — essentially project planning — at my internship and then applied those methods to managing my team for Senior Design.*

When asked how well-prepared participants felt they were for Senior Design, respondents rated their preparedness an average of 7.61 out of 10. No respondents rated their preparedness at less than 5, as seen in Figure 4.

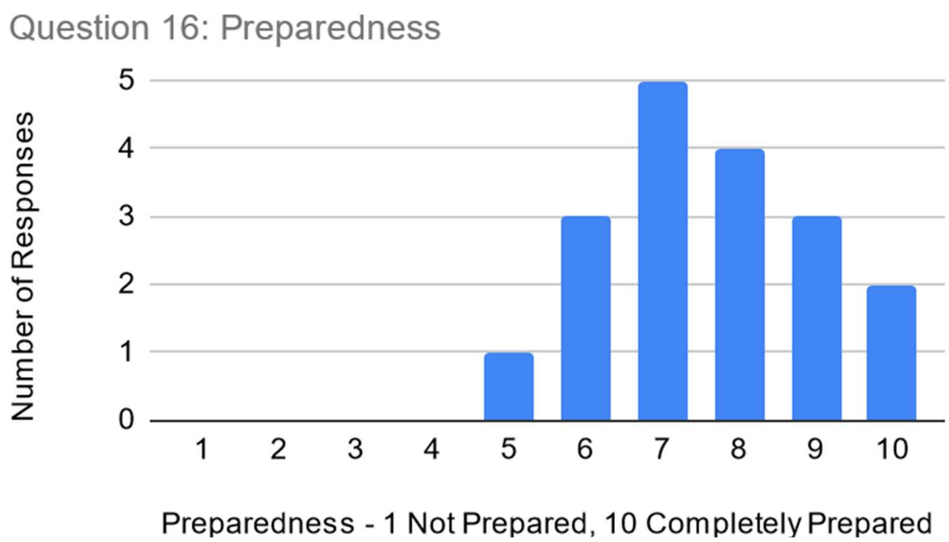

Figure 4. Student Ratings of Preparedness Going into Senior Design

Respondents were also given the option to include any other thoughts or suggestions regarding the Senior Design experience at the end of the survey. A common theme that appeared was students recognizing that one of the purposes of the course is to allow them to make their own decisions and be the experts for their own projects. Again, selected comments are shown below.

- *Maybe the whole point of the class is for you to figure everything out on your own because that's how it is in the real world, but I think a little more guidance would have been nice.*
- *I understand there is a deep a sense of letting the students work from scratch. But I think success would improve if students are shown more past reports earlier of successful projects.*
- *Fortunately, the AEs have to present their projects to a board of experienced engineers at the end of each semester. This really brings up the quality of our projects and pushed us to achieve more.*
- *Senior Design provided a good sandbox to practice making my own decisions, living with the consequences (good or bad), and developing both confidence and humility. It helps to build those skills before my decisions have severe consequences.*
- *I believe that the senior design project is extremely important to engineering curriculum, as it exposes some engineers to their first taste of true project management.*

Case Study 1 – Aircraft

SLU has sent student teams to compete in an annual competition held by Association for Unmanned Vehicle Systems International (AUVSI) for the past several years. In it, students are required to adapt an aircraft to be able to perform all specified mission objectives. Such objectives for AUVSI’s Student Unmanned Aerial Systems Competition (SUAS) involve target detection, payload deployment, and autonomous mission execution. In order to be considered “competitive” in the contest, a previous Senior Design team was employed to design and build a reusable platform for the competition team. This platform served the AUVSI team for five years and was able to help the team to achieve the highest ranking of 14th out of 63 teams.

In achieving this ranking, however, the previous Senior Design platform required significant off-design modifications due to the annually changing requirements. Concern over performance and safety factor arose during one such year of changing requirements and thus adjustments were made to the previous design. These modifications created significant difficulty for the team in the past, so the project being discussed in this case study revolved around a replacement platform. The new platform was to be an overall better design, in terms of manufacturability and performance, thus enabling SLU's team to reach higher rankings in competition. The project also involved manufacturing the new platform.

In order to be confident in the replacement aircraft design, a rigorous approach to stability and control analysis was performed. For this portion of the design process, material from previous courses—like Linear Vibrations, Analysis and Control of Linear Systems, and Stability and Control—was heavily referenced in the design process. However, software analysis of stability and control was not discussed in depth during the courses, which is one place where students needed to fill the gap between coursework and the true design process.

The Advanced Aircraft Analysis (AAA) software was used to get a more robust understanding of the vehicle's stability and control parameters. Hand calculations and a less robust software, XFLR5, were used as well, with similar results obtained with all three methods. While some comparison could be made between all analysis methods, AAA provided results that were more detailed than the other methods. This cross-verification process with the results that all methods yielded allowed for confidence in the AAA results that was not possible using the other approaches. The practice of using this type of software, in addition to the cross-referencing analyses, is not something explicitly taught in typical coursework.

An example of how classwork was successful in leading students into the design project was in the Introduction to Aerospace course, which gave a broad understanding of the problem-solving process as an engineer. This broadened into all courses, including Aircraft Performance which taught the takeoff and landing aspects of designing flight vehicles and aided the students who took the aircraft path in their Senior Design project.

Similar to the stability and control analysis, Computer-Aided Design (CAD) and structural analysis are tasks that were taught only on a surface level in undergraduate coursework. The task of assembling an entire aircraft in a CAD software is a project larger than that done in typical course work. Further, extracting coordinates so that the CAD model could cooperate with the AAA software was another difficult task. This took extended time and effort by the students.

Working more in depth with analysis software is something that was not delved into enough in coursework yet proved to be a significant aspect of the design process.

Case Study 2 – Spacecraft

This case study focuses on a spacecraft mission feasibility study. In this project, the feasibility of a 12U-sized spacecraft whose mission was to perform a soft landing on the lunar surface was analyzed. Unlike the previous case study, this project did not contain a building component; however, there were still numerous obstacles to overcome.

One of the hurdles known by the team going into this Senior Design project was the lack of coursework related to spacecraft design. Because the upper-level required courses tend towards aircraft design—for instance, Aircraft Performance or Stability and Control—teams that complete space-related projects can sometimes feel underprepared or lacking in resources (at least in the experience of the team analyzed in this case study). Prior to the recent implementation of a new core curriculum, aerospace students were only required to take one space-related course (Astrodynamics). Since students are allowed to choose what type of project they want to complete in the Senior Design course, some of the responsibility falls on them in ensuring that they either have enough background knowledge from outside of their required courses going into Senior Design or that they will be willing to work to fill in the gaps.

For students that intend on completing spacecraft-centered projects, the technical electives that they choose can play a large role in preparing for Senior Design. Of the survey respondents that completed spacecraft projects, 88% rated their electives as being more helpful than required coursework. In fact, of the courses called out in Table 1, the only electives that were mentioned were those related to spacecraft design.

The elective that was rated most beneficial was Space Mission Analysis and Design (SMAD), a sentiment shared by those that completed the project discussed in this case study. This elective covers each of the major spacecraft subsystems—power, communications, structures, thermal management, command and data handling, attitude determination and control, and propulsion—as well as an introduction to systems engineering. For a spacecraft design project, it is necessary to analyze and design each major subsystem (unless the chosen project has a narrow focus). For the feasibility study discussed here, the Senior Design project was the first time that the group had to do any design involving communications, power, thermal management, and command and data handling. It was in SMAD that the basics of these subsystems were learned. With the knowledge from the course, first-order budgets for mass, power, and communications were able to be developed, and these budgets were used throughout the entire Senior Design sequence. It should be noted that with the implementation of a new core curriculum at SLU, a course similar to SMAD called Design of Space Missions will be required for all aerospace engineering undergraduate students.

Though the Astrodynamics and SMAD courses laid the foundation for the team to specialize in a spacecraft, there were still many gaps in knowledge that had to be filled by students on their own. For instance, the design of deployable structures and mechanisms is never covered in any classes aerospace engineering students are required to take at SLU (nor in electives known to the authors). Students also had to teach themselves what aspects are of value in various subsystems when conducting trade studies since detailed design of subsystems is not covered in the SMAD elective course, just basic design considerations. Though it was useful to the team to learn these specialized skills on their own, it was often frustrating and time-consuming, which may have an effect on students' contentment with their academic program.

Despite a lack of required coursework focused on space applications of aerospace engineering, many students that complete spacecraft projects benefit from having previous experience with design and build groups. Within the lunar lander feasibility study group, team members had experience with SLU's CubeSat Lab, or Space Systems Research Laboratory (SSRL), and the SLU Rocket Propulsion Laboratory (SLURPL). The survey results showed this type of experience to be the most beneficial in preparing for Senior Design, and that was also true with this team's project. In this case, not only was it beneficial for learning about spacecraft, but also for introducing students to "systems thinking." While there were lessons in the Senior Design course on topics like requirements, functional architectures, and trade studies, students that had experience in these areas from previous design projects had a sizable advantage. Unlike the aircraft case study, at the beginning of the lander feasibility study, there were no requirements or specific mission objectives given; the team started from a blank sheet. Along with the supplemental lessons given during the Senior Design course, the experience acquired from systems-based extracurriculars allowed for the team to develop a mission statement, functional architecture, concept of operations, and requirements with relative ease.

In addition to the technical knowledge gained, having multiple years of experience with SSRL and SLURPL exposed the team to independent problem solving. Much like with Senior Design, these organizations tend to dive into design head-first. Not only did this give students experience with "figuring things out on their own," but it also helped them identify resources that would be useful to them. For example, the SSRL regularly references the *Space Mission Engineering: The New SMAD* textbook. Because the team was familiar with this text, they wasted no time in using it as a primary resource from the beginning of the project.

Another resource that can be of great use to all teams is having a mentor. Of the 18 respondents to the survey, 15 indicated that they had a mentor, with 9 having been assigned a mentor by the course instructors and 6 finding their own mentor. Mentors, in the form of an industry professional or a professor, can provide valuable insight into both the design process and technical information that students might not have due to lack of experience. For this case study, having a mentor was perhaps what helped the team the most. Input from the mentor during weekly meetings was crucial to the team and ensured that they were on the right track with the design. Even when the mentor did not know the answers to the team's questions, they would help find answers. The mentor also helped the team prepare for presentations and throughout the year by giving feedback and preparing them for any questions that might be asked.

Discussion

The existing disconnect between classroom learning and capstone application is hypothesized as being due to a few factors. One such factor focused on here is the specialization aspect of education, where the student transition from course to project is closely related to interest and project choice. This can then impact the student view on the relevance of coursework, as spacecraft teams often do not have an equally robust course background related to their project due to the institution's specialization not lining up with that of the students. While valuable in some ways—in particular, teaching students to learn and problem-solve on their own—the intentional knowledge gap from class to project can be a difficult obstacle for students, regardless of any specific specialization.

There were a few areas that required skills not taught in typical classes. The manufacturing aspect is the largest of these. A metal-working course is scheduled to be taken by all students in the fall of their second year, as seen in Figure 1. However, the skills learned in that course do not translate in a direct way to building an aircraft out of fiberglass, wood, foam, and plastics, skills required for some Senior Design projects. This course is also set so far away in time from the capstone project that it is easy for students to lose their familiarity with the machines.

On the other hand, requiring a workshop class earlier in the curriculum can help enable students to be more involved with clubs and organizations that benefit from this knowledge. For example, some respondents of the survey had some general experience in aircraft construction and project operation from extracurricular groups such as the AUVSI competition from Case Study 1. Unfortunately, not every student is able to be involved in such extracurriculars, and some are not able to apply their club activities to their project at all. This can leave some unprepared for the rigors of manufacturing and design as they approach their project. Because of this, a subsequent elective that follows the first manufacturing course could be offered, as to provide students more hands-on experience and familiarity with methods required for Senior Design.

In some cases, the lack of specialization in coursework makes sense. Certain processes—such as engine testing, test flight procedures, and specific manufacturing methods—are unique to certain projects. On the other hand, there are other processes that are widely applicable and becoming more important to the industry as a whole, such as 3D printing and laser cutting. Therefore, a suggestion that could improve the quality of student knowledge would be to incorporate modern manufacturing into coursework in some way. One way to implement this could be to offer a blend of manufacturing and computer modeling courses that would effectively combine and expand on earlier courses. Further, multiple design projects throughout the curriculum could benefit student learning. This would allow further growth and opportunity to internalize classroom concepts as they relate to the physical world of engineering. An additional manufacturing aspect could be added to existing coursework projects and could also provide students with some preparation for the detailed capstone project later in the curriculum. The more often students are able to work with hands-on tools, whether in manufacturing or learning to use new software, the more prepared they will be for Senior Design.

Perhaps the most valuable aspect of the capstone project is learning the extent to which teamwork is required for success. Engineering is often referred to as inherently team based. The design project is a fantastic way to encourage student growth in this area. While no course will ever be perfect, students can still benefit in a profound way from experiences like Senior Design. Of the survey respondents, 72% said that they consider their Senior Design project to be a success from a technical standpoint, while 100% said that they considered it a success from an educational standpoint. It is clear that despite some shortcomings, Senior Design is still considered a valuable tool to the education of student engineers.

Conclusions

Aerospace engineering is a challenging field to learn as it includes many fundamental topics in addition to aerospace-specific courses. Given the time constraints and content requirements of the typical aerospace engineering program, there is sure to be a gap to bridge between academic content and realistic applications in Senior Design projects. The struggle of constructing that bridge provides an opportunity for growth in the direction of a chosen specialization. Courses leading into Senior Design provide an integral foundation for the holistic elements of the capstone experience. Nevertheless, room remains for improving students' preparedness for the difficult obstacles ahead in their careers.

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Appendix

Table 2. Survey Questions

Number	Question	Type of Response
1	Which courses leading up to Senior Design best prepared you for the class?	Free Response
2	How helpful would you rate your required courses in terms of preparing you for Senior Design?	1-10 Scale (1 Least Helpful, 10 Most Helpful)
3	How helpful would you rate your electives in terms of preparing you for Senior Design?	1-10 Scale (1 Least Helpful, 10 Most Helpful)
4	OPTIONAL: Please provide any other information you think would be useful with respect to courses taken prior to / concurrent with Senior Design.	Free Response
5	Did you participate in any design and build teams prior to or during Senior Design? If so, did you learn anything from this experience—knowledge or skills—that you applied during Senior Design?	Multiple Choice: - No, did not participate. - Yes, I participated, but didn't apply anything to Senior Design. - Yes, I participated and applied skills/knowledge to Senior Design.
6	How helpful would you rate your design & build team experience in terms of preparing you for Senior Design? If you did not participate in a design & build team, please skip this question.	1-10 Scale (1 Least Helpful, 10 Most Helpful)
7	OPTIONAL: Please provide any other information you think would be useful with respect to your design & build experiences prior to Senior Design.	Free Response
8	Did you complete an internship before Senior Design? Did you learn anything from this experience—knowledge or skills—that you applied during Senior Design?	Multiple Choice: - No, I did not complete an internship. - Yes, I completed an internship, but didn’t apply anything from it. - Yes, I completed an internship and applied

		skills/knowledge from it to Senior Design.
9	How helpful would you rate your internship experience in terms of preparing you for Senior Design? If you did not participate in an internship, please skip this question.	1-10 Scale (1 Least Helpful, 10 Most Helpful)
10	OPTIONAL: Please provide any other information you think would be useful with respect to your internship experiences prior to Senior Design.	Free Response
11	What, if any, other experiences did you have prior to Senior Design in which you learned something you later applied during Senior Design?	Free Response
12	Was your Senior Design group assigned a mentor?	Multiple Choice: - Yes, the instructors assigned our group a mentor. - No, the instructors did not give us a mentor. - We had our own mentor that was not assigned by the instructors.
13	What type of vehicle/mission did you design: aircraft, spacecraft, rocket, drone, or other?	Multiple Choice: Aircraft / Rocket / Spacecraft / Drone / Other (Fill-in)
14	Please briefly describe your project.	Free Response
15	What was your role in your Senior Design group?	Free Response
16	How well prepared do you feel you were for Senior Design?	1-10 Scale (1 Not Prepared at All, 10 Completely Prepared)
17	Do you consider your Senior Design course to be a success from a technical standpoint?	Multiple Choice: Yes / No / Other (Fill-in)
18	OPTIONAL: Please provide any other information you think would be useful with respect to the success of your Senior Design experience from a technical standpoint.	Free Response
19	Do you consider your Senior Design course to be a success from an educational standpoint?	Multiple Choice: Yes / No / Other (Fill-in)
20	OPTIONAL: Please provide any other information you think would be useful with respect to the success of your Senior Design experience from an educational standpoint.	Free Response
21	At any point during your Senior Design, were there restrictions due to COVID?	Multiple Choice: Yes / No
22	If there is anything else you would like to discuss, please do so here!	Free Response