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Redefining Student Preparation for Engineering Leadership Using Model-Based Systems Engineering in an Undergraduate Curriculum

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George F. Halow is named Professor of Practice in Aerospace Engineering effective May 1st, 2019 and is specializing in teaching leadership and professionalism in engineering. He is the winner of the 2020 Sigma Gamma Tau Silver Shaft Award as the top teacher in Aerospace Engineering, and the 2021 Aerospace Engineering Department Diversity, Equity, and Inclusion Impact Award.

Prior to his appointment at the University of Michigan, George had a distinguished 31-year career at Ford Motor Company, where he held numerous positions as Chief Engineer of multiple vehicle lines (Expedition/Navigator, Crown Victoria, Grand Marquis, Town Car, and Ranger), several engineering leadership positions in automotive interiors and exteriors, and possesses operational experience in product design, manufacturing, and business & technology strategy.

George has also been a very active mentor and coach, both in industry (serving on multiple personnel development committees and special projects to enhance organizational competency) and in academia (serving as the Ford Executive Champion for University of Michigan Student Teams, and Ford lead recruiter for the Georgia Institute of Technology and the University of Maryland). In addition, he has been a featured guest lecturer numerous times on multiple leadership subjects, and at all levels, at the University of Michigan, the University of Maryland, the Georgia Institute of Technology, Emory University, and Cornell University.

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I graduated from Purdue University in 1985 with a BSME before taking my first job at General Motors. At GM, I worked in engine manufacturing for four years, then spent the following eight years in powertrain development with a focus on noise and vibration. During my career at GM, I received an MSE degree from Purdue through distance learning. In 1998, I left GM to take on a role with Siemens (formerly LMS North America), selling high tech solutions to the automotive industry with focus on Asian auto OEM's. I spent 20 years as a major account manager before changing roles as a project manager for the academic strategy team. I recently retired in January 2021.

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May 24, 2021 – Filed

Abstract

US colleges and universities confer over 130,000 engineering degrees each year. However, while graduating students from top universities possess strong technical skills, there remains a wide gap between industry's expectations and graduating students' capabilities around systems engineering, complex project management, and essential business skills including team leadership, risk-based decision-making, and communication. Unfortunately, formal instruction to address these needs remains lacking at the undergraduate level, leaving students inadequately prepared to meet their employers' expectations upon moving into the workforce.

This paper outlines an undergraduate curriculum aimed at addressing this problem through a systems engineering and leadership pilot course spanning two semesters. Pilot course participants were leaders from three aerospace-focused student project teams (n = 20), each designing an aircraft (two drone teams, and one electric-powered airplane). The course provided training on key systems engineering tools and process elements, as well as essential leadership and business skills, guiding teams as they developed their craft from requirements to competition.

To accomplish this, the course implemented a lab sequence dedicated to Model-Based Systems Engineering (MBSE) in combination with teachings and team-based assignments revolving around critical Systems V-based engineering tools and processes, including risk management tools and process, project management, and Six Sigma-informed quality and test execution. Course pedagogy—supplemented by a number of guest lectures by distinguished industry practitioners—informed and directed project teams to ensure product excellence and program health. How effectively students applied these tools and processes was then assessed by panels of industry and faculty judges at three team design review events throughout the course.

To ascertain the effectiveness of the teachings and enable continuous improvement to the curriculum, we examined student survey responses, quantitative scoring and comments by judges during team design reviews, and student teams' performance in their respective competitions. In addition, we incorporated feedback from experts in the aerospace field in response to course teachings and outcomes.

Finally, this paper outlines future plans for scaling the curriculum to a full hands-on, lab-based experiential learning platform. It also captures plans for future expansion to a full course series (3 courses) and other engineering disciplines at the undergraduate level.

Graduate applications are under consideration, but are beyond the scope of this effort and paper.

Background and Motivation

Many companies indicate that, although new graduates with bachelor's degrees in engineering disciplines possess exceptional technical talent and knowledge in the fundamental theoretical elements of engineering (structures, fluid mechanics, propulsion), many fall short relative to capabilities around systems engineering, complex project management, and essential business skills. These issues are not new and have been chronicled for decades. The quote below, from a 2000 study, captures many of these shortcomings:

> "…**Deficiencies in engineering education** have been exhaustively enumerated in recent years. Engineering schools and professors have been told by countless panels and blue-ribbon commissions […] that we must **strengthen our coverage of fundamentals**; teach more about **"real-world" engineering design and operations**, including **quality management**; cover more material in frontier areas of engineering; offer more and better instruction in both **oral and written communication** skills and **teamwork** skills; provide training in **critical and creative thinking** skills and problem-solving methods; produce graduates who are conversant with engineering **ethics** and the **connections between technology and society**…" [1]

More recent data suggest that academia is not sufficiently moving the needle. Figure 1, below, is an excerpt from the 2017 Tech-Clarity report "Close the Engineering Skills Gap" [2] where leaders of companies ranging from aerospace, automotive, machinery, energy, and consumer products industries indicate areas in which academia is not preparing students well for future employment.

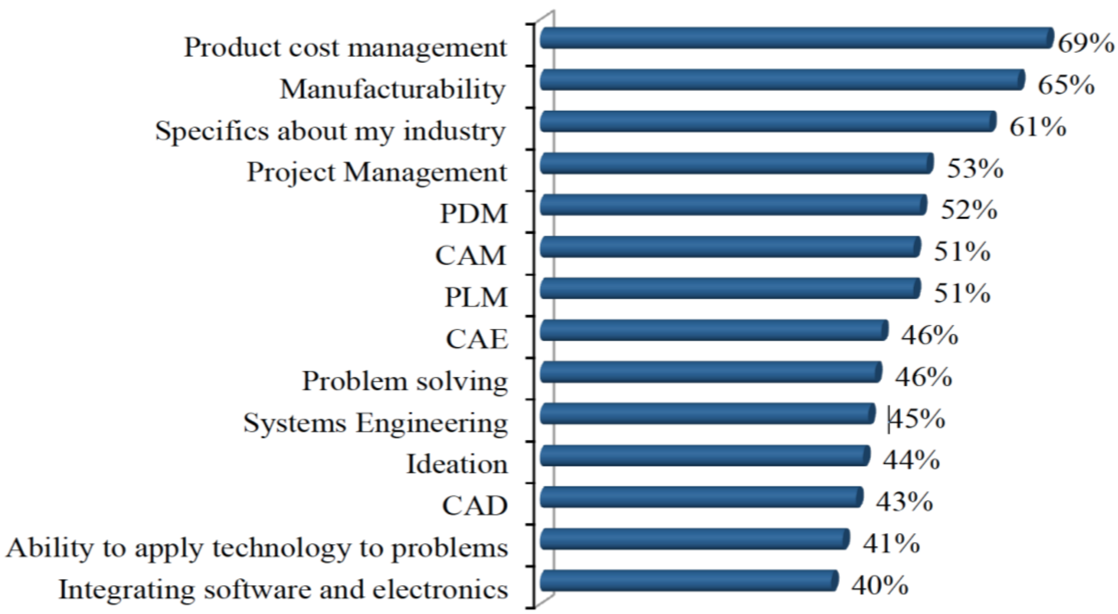

***Figure 1:** Top Skills Schools Do NOT Prepare Students Well For [2]*

Additionally, Listing 1 provides quotes from individuals involved in the present activity around accelerating the pace of driving essential business skills into the undergraduate engineering curriculum.

Listing 1: *Quotes Regarding the Skill Gap*

- "...For many years, the University of Michigan Aerospace Engineering Industrial Advisory Board have praised the University of Michigan for graduating the most technically sound engineers, but have also consistently voiced concern that graduates lack the 'essential' business skills many organizations desire for leaders of their technical organizations. This problem is not new, and is not isolated to the University of Michigan, but we now see initiatives spearheaded by Professors Tony Waas and George Halow to address this, and we are delighted by it. "
—Kevin Michaels, Managing Director of Aerodynamic Advisory consulting firm, and University of Michigan Aerospace Engineering Industrial Advisory Board Chair

- "Academic institutions around the world are doing an outstanding job of preparing Engineers for the technical challenges they'll face. What's missing is that the process of engineering has changed dramatically. No longer do engineers work in isolated teams focused on their engineering discipline. No longer are Systems Engineers a function that just aligns requirements across disciplines. Today's engineers are immersed in systems thinking. They are immersed in the entirety of the system they are working on regardless of the discipline they focus on. Academia has to catch up with the way engineers really work today—and this program is exactly what's going to help the University of Michigan close that gap." *—David Taylor, Vice President Industry Strategy, Marketing, & Global Execution, Siemens*

- "... [The practical applications] skills gap is definitely one of the main challenges in industry [...] Digitalization and the new speed of innovation are creating more complex engineering challenges that require out-of-the-box thinking. [...] This not only includes understanding multiple engineering disciplines and mathematics and physics theory, but being able to communicate effectively, integrate into a team successfully, and use a variety of tools efficiently." *—Gil Morris, (retired) Siemens Systems Engineer [3]*

- "The Aerospace Department at UM has recognized the gap in employers' expectations and conventional university education and is committed to adopting contemporary practices in industry and instilling within our graduates the values, technical skills and competencies needed to succeed in the world when they leave UM. Engaging our industry partners and the UM Aerospace Industrial Advisory Board in doing this is a priority for us. We stand committed to ensure that our graduates get the best preparation to become successful engineers in the workplace." *—Tony Waas, Department Chair, University of Michigan Aerospace Engineering*

- "As an industry recruiter, I could tell within the first 5 minutes of an interview, without even looking at the resume, whether someone had robust student project team experience by the way they answered questions, engaged, understood technical work in the broader context of delivering value, in teams, on time and on budget. Unfortunately, those skills were more the exception rather than the rule in my interviews of students."
—George Halow, Professor of Practice, University of Michigan Aerospace Engineering, and former Chief Engineer, Ford Motor Company

This paper outlines a new course launched at the University of Michigan to respond to these crucial industry-identified gaps. The course provides training on key systems engineering tools and process elements, as well as essential leadership and business skills, guiding teams as they develop operational prototype aircraft from requirements to competition. To accomplish this, the course implements a lab sequence dedicated to Model-Based Systems Engineering (MBSE) in combination with teachings and team-based assignments revolving around critical Systems V-based engineering tools and processes, including risk management tools and process, project management, and Six Sigma-informed quality and test execution. Course pedagogy—supplemented by a number of guest lectures by distinguished industry practitioners—informs and directs project teams to ensure product excellence and program health.

The course provides these skills through application on student project teams, which are a natural vehicle for such topics because these teams are a microcosm of a product development activity in a large industrial organization.

This course was preceded by, and builds on, exceptional, hands-on, project-based courses created by other University of Michigan Aerospace Engineering Professors [4], primarily Peter D. Washabaugh, Timothy Smith, the late Luis Bernal, Mirko Gamba, and James W. Cutler. These professors have built strong and very popular design/build/test/fly experiences, providing a solid foundation and consulting for the present work.

Additional consulting to help shape the course was provided by leading faculty and industry experts, including:

- University of Michigan College of Engineering – Jim Bagian, A. Harvey Bell, Art Hyde
- University of Michigan Ross School of Business – Eric Svaan
- Industry – Phil Condit, former Chairman and CEO, Boeing, Lisa Drake, Vice President Purchasing and COO, Ford North America, and several members of the University of Michigan Industrial Advisory Board, notably Karen Albrecht, a former Lockheed Martin Executive

Course Strategy

The fundamental premise of this course is to establish and deliver "just-in-time" training in both systems engineering and the essential business skills to deliver a highly complex technical project. Upon course completion, students should have the skills to:

- Confirm a product or technical project meets customer needs and/or requirements using disciplined tools and processes
- Establish a detailed project plan, with dependencies, key milestones, go/no-go decision points, and backup plans
- Conduct formal and effective gateway and design reviews, with objectives, success criteria, and standard communication proformas
- Create and deliver effective technical and business presentations, knowing the audience and tailoring the messages appropriately
- Decide which manufacturing process(es) to use for specified applications, understanding the benefits and limitations (including cost, timing, quality)

- Use industry standard tools to establish potential failure modes, and eliminate/mitigate risk through clever design and validation practices
- Establish and sustain effective teams, including valuing diversity (gender, ethnicity, operating styles, communication styles, diverse viewpoints)

The course is built around a typical product development cycle, consistent with most industrial product development organizations, and mirrored by student project teams. Figure 2 illustrates a graphical representation of such a cycle for a student project team.

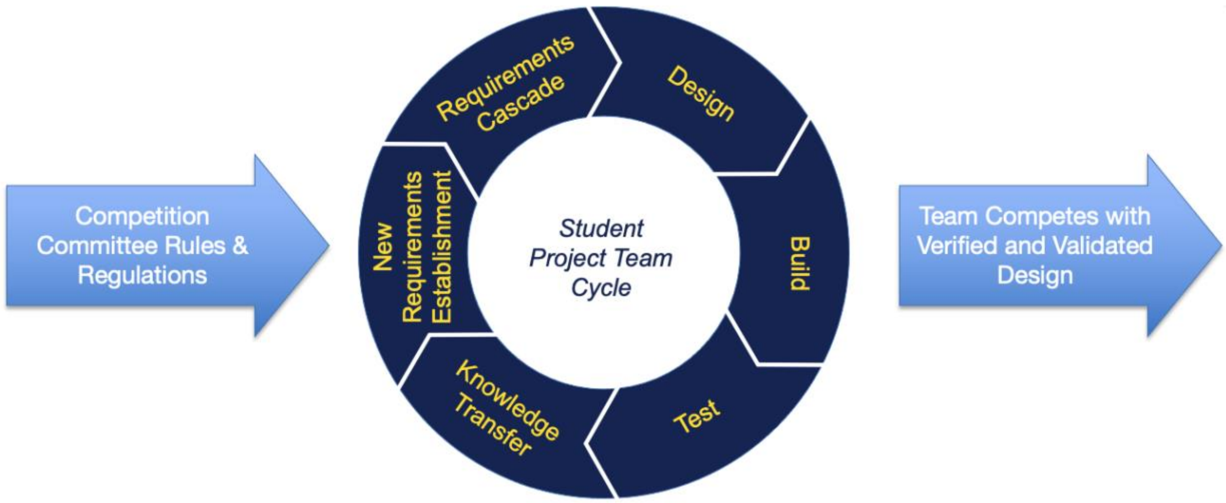

Figure 2: *Product Development Cycle Mapped to Student Project Teams*

It then maps a single cycle to a Systems V development process, spanning an academic year (September - April), which is generally aligned with the majority of student project teams' development calendars. This can be seen in Figure 3.

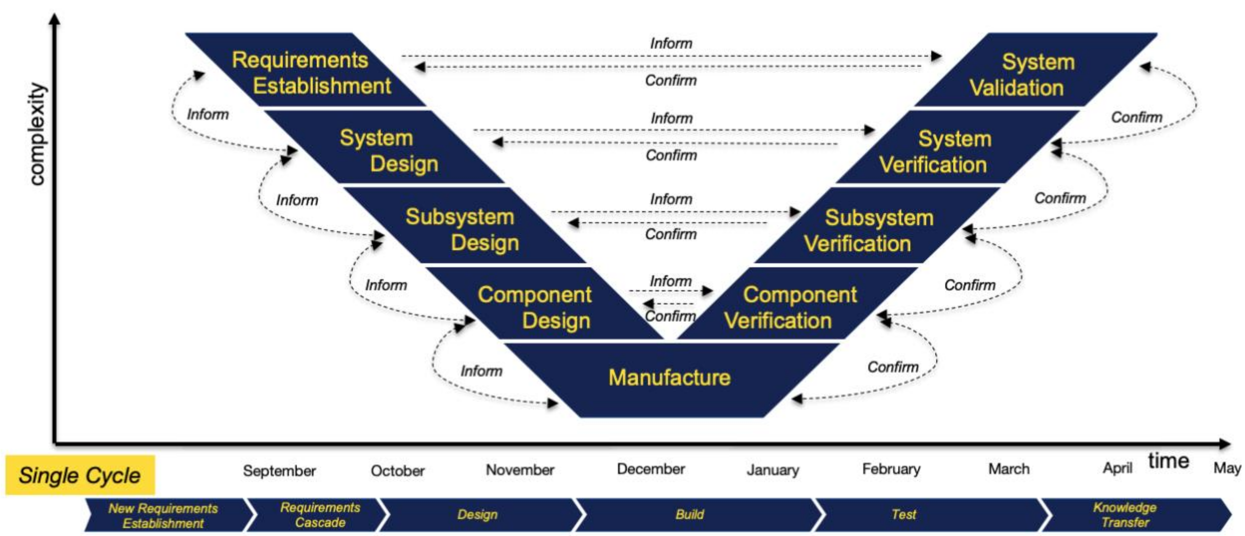

Figure 3: *Systems V Relative to Course Timing*

Student project teams are the appropriate cohort for this course, and application of its teachings, because:

- They have a heavy reliance on teamwork, organization, and trust.
- They have a work breakdown structure which mimics what a typical complex product development cycle looks like in an industrial environment, albeit on a smaller scale.
- Their success is largely measured by how their team's final product performs in competition.
- They have specific deliverables for their respective competitions, with given and inviolable timing. These are also paired with a known set of basic "customer" requirements (often via competition rules) provided with the request of these deliverables.
- They are complex, multi-domain systems involving domains such as aerodynamics, structures, control systems, propulsion, and safety.
- Their projects require a disciplined process of moving through requirements, design, systems integration, simulation, manufacturing, verification, validation, and flight.

The course is broken down into five (5) components:

I. Design
II. Manufacture
III. Verify
IV. Fly
V. Sustain

Each component is comprised of pedagogy created through real-world experiences and enhanced by relevant guest speakers from industry, government, and academia. A timeline of how components, topics, and assignments are distributed throughout the year is exhibited in Figure 4.

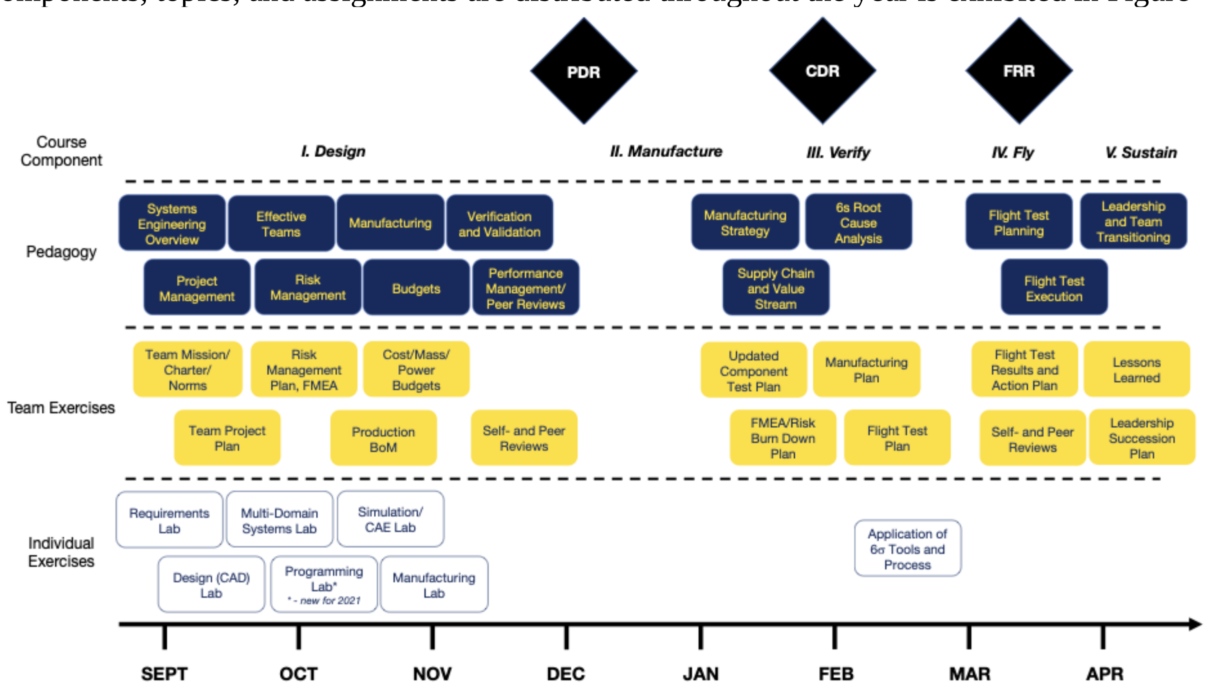

Figure 4: *Timeline of Course Topics and Major Deliverables*

Component I — Design: The Design Component consists of tools, process, and leadership pedagogy in order to teach students fundamental skills in simultaneous and systems engineering—modeled after the Systems V and Model-Based Systems Engineering (MBSE). In this component, students develop a system, starting with requirements in Capella, an open-source requirements modeling tool, and then progress through design, creation of a multi-domain system, simulation, and manufacturing in Siemens Teamcenter. This provides practical application experience on a known and simple system; they then apply the tools on their student team projects.

The Design component is the longest course component by far, spanning a full semester.

Why? A substantial amount of manufacturing and product cost is fully determined in design; in the book "Design for Manufacturability," author David M. Anderson estimates that 80% of the cost is committed in design as seen in Figure 5 on the right [5].

While the precise figure may vary, in most industries involving complex systems the overwhelming majority of the manufacturing bill of process, and thus cost, is locked in during the design phase.

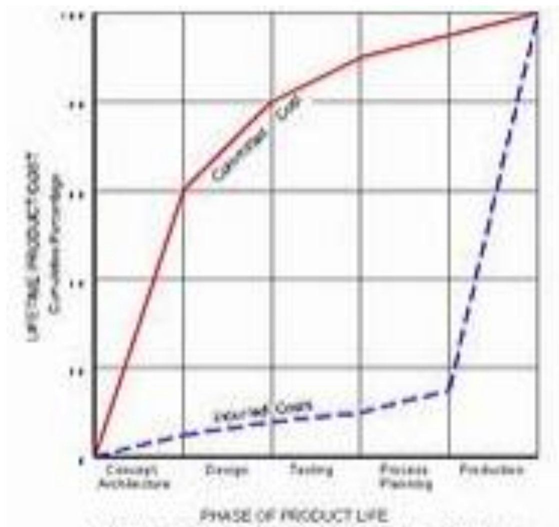

Figure 5: *Committed and Incurred Costs, by Product Development Phase [5]*

The main elements of the Design component include:

- <u>Systems Engineering and the Systems V</u>—This section is designed so students are able to put the course teachings, assignments, and project work in context with the Systems V and fundamental systems engineering principles. Accompanying these teachings and assignments, students were required to complete a sequence of lab assignments designed to familiarize them with key MBSE tools and processes. In this lab sequence, students use industry-standard software to move through each stage of the design cycle for a propeller and motor system. Each lab targets a specific aspect of the design cycle, relates it to the relevant MBSE tools and processes, and walks students through a set of exercises that will enable them to learn how to implement these. Specific lab topics and exercises are outlined in Table 1; these are virtual in the inaugural year of the course due primarily to COVID-19 restrictions; subsequent years will include a physical lab component.

Table 1: *Breakdown of MBSE Lab Sequence*

Lab	Desired Student Outcomes	Exercises Implemented to Reinforce Outcomes
Lab 495-01: Requirements	● Understand the practicality and purpose of MBSE tools ● Apply MBSE framework to cascade project team requirements and capture first step of Systems V	● Create a guided requirements model ● Model team's requirements
Lab 495-02: Computer-Aided Design (CAD)	● Understand the CAD modelling workflow ● Understand how components come together in an assembly ● Apply CAD tools and skills to model components for their project team	● Model a basic 2D extrusion ● Model a complex propeller ● Assemble propeller model with other parts
Lab 495-03: Multi-Domain Systems	● Characterize the behavior of a multi-domain system ● Identify exchanges that take place between components in a multi-domain system	● Model a multi-domain system ● Add specifications for the system ● Simulate system with specifications
Lab 495-04: Computational Fluid Dynamics (CFD) and Finite Element Method (FEM) Simulations	● Understand the methodology and fundamental physics behind CFD/FEM simulations ● Apply CFD/FEM tools to solve engineering problems ● Effectively apply these simulation skills to components or models for their own project teams	● Run CFD analysis on a basic 2D extrusion ● Run CFD analysis on 3D propeller model ● Generate FEM stress and displacement simulations for the propeller model
Lab 495-05: Manufacturing with Computer Numerical Control (CNC)	● Understand how to use CNC tools and programming to manufacture complex parts ● Apply a cost-benefit analysis to optimize manufacturing decisions	● Generate CNC cutter tool paths to manufacture propeller model ● Create a cost-benefit analysis comparing two manufacturing methods across multiple scenarios

- Project Management—Students learn tools, processes, and behaviors that enable effective management of a complex project, including work breakdown structure, tasks, task relationships, critical paths, and resource constraints. The exercise includes developing an overall project plan for their team aircraft.

- Effective Teams—Students learn how to manage through the five stages of team development, which are vital to establishing exceptional team dynamics. The teams develop a charter and use Myers-Briggs surveys to better understand each member's operating styles. They also learn techniques for increasing diversity, both on the team and in leadership positions, and discuss ways to incorporate input from all team members. Later in the semester, students learn about the performance management process, including completing self- and peer evaluations to provide constructive feedback on individual and team performance improvement. Peer review results are factored into students' grades.

- Risk Management—Students learn the importance of hazard identification, risk analysis-informed prioritization, and decision making that enhance design robustness, tools, and processes including a Risk Management Plan and a Failure Modes & Effects Analysis (FMEA). Students then apply the teachings to develop their own Risk Management Plan, FMEA, and preliminary Verification and Validation (V&V) plan for their respective aircraft.

- Budgets—Students learn how to balance top-down targets with bottom-up status, and apply the learnings to develop cost, mass, and power budgets for their respective aircraft. They also learn about provisions (margins), and how much provision is appropriate to carry and then release throughout the product development process. They also gain exposure to Generally Accepted Accounting Principles (GAAP) in developing and managing their cost budgets.

- Manufacturing—Students learn basic technical and commercial elements of the manufacturing process, including fundamental manufacturing techniques for metals, plastics, electronics, and composites. Furthermore, they learn basic methodology on how to choose the right material and manufacturing technique for a given application. Finally, they learn the basics of fixed, variable, total, and average costs, and apply these learnings to choose the most efficient manufacturing process given a set of input assumptions and volumes. Exercises include creating a manufacturing plan for all of their key components, as well as developing cutter paths in CAD for an injection mold cavity; this occurs in Lab 5, which is described in Table 1.

- Verification and Validation—Students learn how to deliver the plans for the "right side of the Systems V"—development of the Verification and Validation (V&V) Plan based on the design requirements, before actually building hardware. This element includes brief teachings on repeatable and reliable (R&R) evaluation methods and how to eliminate/manage noise factors. Students apply learnings through a preliminary V&V plan for their aircraft and a risk "burn-down" plan to demonstrate how risk is mitigated through specific design robustness actions.

Additionally, students learn how to create and conduct an effective design review using templates, checklists and scorecards, and effective organizational and communication techniques (including capturing agreements, outcomes, and follow-up assignments). Component I culminates in a Preliminary Design Review (PDR), complete with scorecards and design readiness assessments, presented to a panel of judges composed of industry experts. At the end of the PDR, the judges fill out a questionnaire, and the results are then factored into the students' grades.

Component II — Manufacture: More detail on manufacturing strategy and implementation is provided, as well as a lecture on value stream and supply chain management. Students analyze make vs. buy decisions on some of their aircraft components, as well as the rationale in making such decisions, designing parts to target (including benchmarking), and the value of interactive teamwork with suppliers in achieving efficient designs. Outputs are updated manufacturing plans including make vs. buy assumptions.

Strategic make vs. buy factors (internal core capability, competitiveness of the market, and long-term strategic fit with the enterprise) are taught to paint a complete picture of a value stream in a complex product development organization, even though these are generally out of scope for their one-off competition aircraft.

The Critical Design Review (CDR) occurs early in this component, after the first "make vs. buy" discussions, but before formal manufacturing activity. (Note: some preliminary manufacturing is covered in the Design component, particularly around selection of materials and manufacturing technology/process.)

Component III — Verify: Students execute the V&V plans they developed in the Design component in order to verify that components and systems meet their requirements. They learn analysis techniques rooted in Six Sigma principles in order to identify and correct issues found in testing to more directly meet product requirements. Students learn how to apply fault trees (fishbone), "5 Why", is/is not, pareto charts, and scatter plots, and then individually apply these methodologies to distinct test failures from their V&V plan.

The teams will then update their V&V plans and risk burn-down plans with the results of their testing and evaluations.

Component IV — Fly: Students learn how to establish a flight test plan to validate all systems requirements which have not been verified through component testing. Students learn how to prepare the test plan, execute the test plan, perform in-flight measurements, and then summarize results to confirm all system requirements have been met.

The Flight Readiness Review (FRR) occurs in the middle of this component, after the flight test plan has been developed, but before execution. Similar to the PDR and CDR, this is judged by a panel of industry experts, whose feedback is factored into the students' grades.

Upon successful completion of FRR, students will perform flight testing, make measurements, analyze and summarize results, and prepare themselves for their formal team competitions.

Final course self- and peer reviews (graded) also occur at the end of this component.

Component V — Sustain: Finally, students receive tools and process coaching on how to sustain a team and associated culture of excellence, including lessons learned/knowledge capture, selecting and grooming future leaders, team performance in transition, and reinforcing an ongoing culture of diversity, equity, inclusion, professionalism, ethics, and excellence.

Students also identify the next academic year's team officers and develop recruiting plans to replace students who are graduating. Emphasis is placed upon individual performance, readiness for leadership positions, and reinforcing diversity. Students will also create development plans for future officers and subsystem leads.

Replicating the Workplace: To further mirror "real-world" experiences, multiple processes are invoked (some of which were outlined in prior sections, but are summarized here for completeness):

Guest Lectures by Senior Experienced Practitioners: While most of the lectures were delivered by the course instructor, many senior-level experts were enlisted to provide lectures on key topics, listed below:

- <u>Systems Engineering</u> — Art Hyde, University of Michigan Professor of Practice with over 35 years automotive experience in leadership roles
- <u>Project Management</u> — Eric Svaan, Professor from the University of Michigan Stephen M. Ross School of Business
- <u>Teaming</u> — joint between Phil Condit, former chair and CEO of Boeing, and the course creator/Principal Investigator (George Halow)
- <u>Risk Management</u> — Jim Bagian, University of Michigan Professor, two-time Space Shuttle astronaut, Founding Director of the VA National Center for Patient Safety, and Founding Director of the University of Michigan Center for Risk Analysis Informed Decision Engineering
- <u>Verification and Validation</u> — Harvey Bell, Professor of Practice with 40 years of automotive experience in leadership roles
- <u>Sourcing Strategy and Value Stream</u> — Lisa Drake, Vice President, Purchasing and COO, Ford North America

Judged Design Reviews: Student teams go through a structured, NASA-informed aerospace design review process, consisting of Preliminary Design Review (PDR), Critical Design Review (CDR), and Flight Readiness Review (FRR). Design Review deliverables are created using industry best practices derived from partner companies, which guide teams on how to robustly pass the gateway. In addition, these reviews are judged by a panel of industry experts from partner companies and judge input via formal questionnaire is factored into students' grades.

Self- and Peer Evaluations: Each student must independently complete a self-evaluation in addition to peer evaluations for each of their teammates in the course. Evaluation questions range from technical competence, leadership competence, teamwork, strengths, and opportunities for improvement. These results are then factored into students' grades.

Performance in Competition Evaluations: Each team was given a "performance bonus" incentive: if their craft finished first, or in the top 5%, of their main competition, each student on the team would receive an automatic 2% increase in their final grade.

Team Performance

The course clearly had a dramatic impact on student team performance, borne out both by objective team finishes, and in subjective comments and reports by both judges and students.

There were three (3) teams in the course:

1. MACH – twin-engine, propeller-driven fixed-wing aircraft (5' wingspan)
2. Michigan Drone Racing (MDR) – small custom-designed drone aircraft with a 20:1 thrust-to-weight ratio
3. Michigan Vertical Flight Technologies (MVFT) – a tilt-rotor tri-copter with autonomous flight capability

Of these:

- MFVT finished 1st overall (amongst 7 total teams*) in an all-new Vertical Flight Society international Preliminary Design Review (PDR) competition in December, 2020
- MACH finished 1st overall (amongst 93 total teams) in an international AIAA Final Design competition in March, 2021
- MVFT finished 1st overall (amongst 7 total teams*) in the VFS Final Design competition in April, 2021

*- *as this was the first year of the VFS competition, only 7 teams participated*

Judge feedback from the course-sponsored design reviews (PDR, CDR, FRR) was compelling – including observations of the dramatic improvement in maturity of all teams through the process, for example ("at PDR, I felt as if some teams were just checking the box; by CDR and FRR, I could tell all the teams totally 'got it'"), and a comment from one judge at FRR ("these reviews are better than what I get from most of my engineers"), a sentiment echoed by many.

In the internal course design reviews (PDR, CDR, FRR), the judges rated the students on six questions ranging from quality of design review, level of program risk, degree of team cohesion, and likelihood of success. For each question, the judges rated the students on a Likert scale from 1-5 – again with the results factored into the students' grades. Here is how the teams performed:

Team	PDR	FRR	FRR B/(W) than PDR
MACH	4.3	4.8	0.5
MDR	4.0	4.8	0.8
MVFT	4.2	4.9	0.7

Course Feedback

As this course is a significantly new and complex undertaking, several modes of solicited and unsolicited feedback were studied to identify successes and areas for improvement:

- Student competency surveys
- Student lab assignment evaluations
- Student course evaluations
- External feedback and commentary

We have included both qualitative and, where available, quantitative data. Since the sample sizes were small, we include the quantitative data for reference, but our conclusions and recommendations are informed primarily by the qualitative input.

Student Competency Surveys (Solicited): A PhD student from the University of Michigan College of Engineering, Cassandra Woodcock, is studying the efficacy of educational outcomes and was enlisted to conduct "competency" surveys. She surveyed the students at the beginning and end of each semester on four major dimensions—leading and working in teams, risk management, leadership, and systems thinking—to assess at what level the students entered the course, and how they progressed throughout it.

These four dimensions were defined for the students before taking the survey as follows:

a. <u>Leadership</u> – Cultivating an environment that collectively develops a shared purpose and inspiring others to work toward it.
b. <u>Teamwork</u> – Working to define and achieve a shared goal by leveraging individuals with different perspectives, roles, responsibilities, and aptitudes to overcome and use conflict to their advantage to create a more robust solution.
c. <u>Risk Management</u> – Ability to critically assess available information, identify vulnerabilities and take action despite uncertainty, manage outcomes, and learn from potential and actual failures as well as from successes.
d. <u>Systems Thinking</u> – Ability to recognize and appreciate the complex structures and their interconnectedness which are embedded in a system while maintaining a view of the highest level objective to be achieved.

The survey consisted of previously established Likert-like, self-report questions (5-point scale) related to development within the dimensions [6], [7] and two open-ended questions related to each dimension. Qualitative responses were quantified using a 3-point rubric that assigned students a 1 if their response was considered at an exploring stage of competency development and a 3 if they were at a high level (explaining) of competency development. Descriptive statistics (averages) of the Likert and quantified qualitative responses are presented in Table 2.

***Table 2:** Quantitative and Quantified Qualitative Survey Responses*

	Competency Dimension	Pre-Course Response (n = 12)	Post-Course Response (n = 12)
Quantitative Likert-Like Scale Scores (1-5)	Leadership	3.9	4.0
	Teamwork	4.0	4.4
	Risk Management	3.3	2.7
	Systems Thinking	3.7	4.4
Quantified Qualitative Responses to Open-Ended Questions (1-3)	Leadership	1.63	1.92
	Teamwork	2.25	2.38
	Risk Management	1.66	2.50
	Systems Thinking	2.17	2.42

Legend:

(red)	Post-course scores lower than pre-course scores
(white)	Post-course scores within 5% of pre-course scores
(light green)	Post-course scores greater than 5% improvement upon pre-course
(green)	Post-course scores greater than 10% improvement upon pre-course

Significant improvements in sophistication and maturity of responses was seen virtually across the board. In both Teamwork and Systems Thinking, students felt they learned and matured (as evidenced by their qualitative responses. While students saw very small improvement in their leadership capabilities, their qualitative responses demonstrated greater improvements vs. their perceptions. Relative to the Risk Management dimension, students rated themselves lower at the end vs. the beginning of the course, which is largely explained by the fact that, coming in, students had no idea of the breadth and depth of risk management tools and processes ("you don't know what you don't know")—confirmed subjectively in a post-survey discussion with the students. Their qualitative answers demonstrated substantial improvement -- by far the most significant improvement amongst all dimensions.

Quotes with the corresponding scores from the open-ended questions on the survey have been provided to demonstrate this substantial improvement in the four dimensions (reference Table 3, below). In most cases, the improvements are compelling, as evidenced by the sophistication and maturity of the answers after the two-semester long course.

Table 3: *Qualitative Responses Demonstrating Competency Growth*

Competency	Pre-Course Response	Post-Course Response
Leadership	An engineer might use their leadership skills when assigning work to others in a project. They will be the ones that oversee most of the project and ensure that the work is getting done. I would identify the engineer-leader as the person who is communicating the most with others. (score = 1)	In a dispute between two team members over any given issue it may be necessary for an engineer-leader to step in and have an unbiased opinion that helps all parties involved put aside their differences and come to the most logical conclusion based on the facts and engineering work that has been done. An engineer-leader is usually fairly easy to spot because they are able to guide people in the right direction without having to force them to do what they want. (score = 3)
Teamwork	As a team, completing a craft we're proud of in time for the competition would be a success, even if we don't win/place. It would only be a success if all the team members felt like they contributed to that outcome. (score = 2)	... I would define success for my team as seeing student members from multiple disciplines working together on the various sub-teams to design, build, and test a working & competitive aircraft for our competition. I want to see everyone voice their opinions based on their expertise and have an open environment for dialogue that can constructively poke holes in all ideas and designs to come up with a product that everyone on the team is proud of. (score = 3)
Risk Management	I would be willing to take a risk if the safety of another person/member is not affected by the choice. For instance, we can take a risk with a certain design choice if the system is still safe. Also, with making a risk, I would have a back-up plan for if that choice yielded negative results. (score = 1)	A risk can be justified once it has significant analysis and research behind it to identify failure modes. The failure modes then need to be analyzed to determine how they can be prevented and how likely they are to occur so mitigations can be determined. The risk is only justified when there is enough confidence that the benefits outweigh the outcome from the potential failure and there are enough mitigations in place to reduce the severity or probability. (score = 3)
Systems Thinking	I think about everything that I have to do for that project, then I break down the tasks into sections, and start working on them one by one, checking each thing off my list. (score = 1)	The team starts by collecting all of the competition requirements and scoring parameters, then builds on those to create internal requirements that we feel improve the team's knowledge and capabilities. With this in mind, each sub-team conducts trade studies that guide a decision matrix to determine the high-level aircraft configuration. Then, each sub-team can begin designing their sub-system while regularly updating the rest of the team. Systems-associated members work with all sub-teams to ensure proper integration and track a sub-system's success to the high-level goals. As designs are completed, they are analyzed and simulated under the expected aircraft operating conditions and optimized from there. After design is complete, sub-system testing begins to ensure that everything is working as expected and adjust anything that isn't. Finally, the competition aircraft can be manufactured and full-system testing can begin. After initial tests to ensure basic functionality, more complex tests will be conducted until the aircraft has been fully validated for competition flight and is ready to compete. Interspersed in this process is a Preliminary Design Review, Critical Design Review, and Flight Readiness Review in order to get outside input on the details of the design and team operations, helping to find potential failures and receive guidance on process management. (score = 3)

Additionally, three more questions were posed to students, seeking qualitative information on the efficacy of the course teachings, and how the students felt they could use the teachings in their careers:

- Thinking about your AERO495 experience this semester, what are 2-3 examples of how what you learned in the following “essential business” topics impacted the design and/or design process for your competition craft?
    - Risk Management and Systems V were cited by most respondents, indicating how impactful those learnings were on their design processes
    - More sophisticated teaming and budget tools were also cited as impactful and beneficial
    - More disciplined Project Management and Verification & Validation were also cited by some respondents

- What are 2-3 examples of how you were able to use the following MBSE tools and/or processes in the design of your competition craft? How did they impact the design and/or design process?
    - Requirements and CAD appeared most in student responses as elements of the MBSE lab sequence which were most useful to their design efforts
    - Manufacturing also was cited numerous times, and notably being crucial to robust and smart design practices

- Of everything we covered during the first semester, which 2-3 topics ("essential business," MBSE, or other) do you expect to find most useful when you graduate and enter the workforce? Why?
    - Most topics were cited multiple times
    - Requirements received the most comments, followed by Risk Management and Project Management
    - CAD, Simulation, Manufacturing, Systems V, Verification & Validation, and general Design Review decorum were also mentioned frequently

These qualitative responses demonstrated that the course teachings did substantially inform student projects and are expected to play a significant role in future endeavors outside the classroom (specifically internships and full-time employment).

Student Lab Assignment Evaluations (Solicited): To evaluate the effectiveness of the lab sequence, and students’ comfort levels with the tools introduced in each lab, students were required to complete a six-question survey (n = 22).

The first two questions were quantitative self-assessment questions:

- For each lab, did you feel that you had enough time to complete the assignment given its scope and length?
    - Students were able to respond on a Likert scale of 1-5, with 1 denoting too little time and 5 denoting too much time. The mean score for each lab is included in Table 4, below; all labs were ranked within the “appropriate amount of time” band except for the Simulation lab, which is undergoing some simplification around instruction and output for subsequent years.

Table 4: *Assignment Timing*

Lab Assignment	Mean (5-pt scale)
Lab 1: Requirements	2.91
Lab 2: CAD	3.05
Lab 3: Multi-Domain Systems	3.14
Lab 4: Simulations	2.09
Lab 5: Manufacturing	3.09

- For each lab, how knowledgeable do you feel about the topics covered, in light of the depth/scope of the assignment given?
  - Students were able to respond on a Likert scale of 1-4, with 1 denoting low knowledge and 4 denoting expert-level knowledge. The mean score for each lab is included in Table 5, below. The target score for the labs is a minimum score of 3; Labs 1, 3, and 4 fell below this. This can in part be attributed to the virtual format of the lab sequence in year 1 of the course; physical lab components, plus additional enhancements, are planned for year 2 and beyond.

Table 5: *Self-Assessed Knowledge Level*

Lab Assignment	Mean (4-pt scale)
Lab 1: Requirements	2.73
Lab 2: CAD	3.36
Lab 3: Multi-Domain Systems	2.55
Lab 4: Simulations	2.5
Lab 5: Manufacturing	3.09

Additionally, four qualitative questions were included in the survey to provide further insights:

- What were your favorite 2-3 things about the lab sequence and why?
  - The most cited response was the mix of skills and variety of disciplines covered, and the fact that these are quite unique from the other lab courses they have had at the University
  - Requirements and Manufacturing received specific mention as unique and valued learnings

  - A majority specifically indicated they enjoyed doing the work in the lab sequence, and felt they got a lot out of it

- If you could change any 2-3 things about the lab sequence, what would they be?
  - Clarity and simplification in the Simulation lab was cited most often as something which would enhance the sequence
  - Other minor administrative elements such as increased office hours were also cited as ways to improve the learning experience (part of this can be explained by the virtual nature of office hours due to COVID-19, but other actions such as increased office hours during non-lab periods, and enhanced post-lab explanations, will be invoked due to the fact that each subsequent lab builds upon its predecessor)

- What would you have liked to learn/do that the labs didn't cover?
  - Having a physical lab component was noted by most respondents
  - Geometric Dimensioning & Tolerancing (GD&T) was cited by one respondent

- Do you have any other ideas, comments, or concerns regarding the lab sequence?
  - Responses were wide-ranging, including a desire to return to an in-person format post-COVID-19
  - Many other responses here were previously covered in prior questions

To remedy concerns around Lab 4 (Simulations), this lab will be re-designed, although still focused around the same content. In addition, a GD&T section will be added to the manufacturing lab. Timing throughout the lab sequence will also be adjusted in accordance with student responses. Finally, although this was not covered in the surveys, a programming and controls lab will be added to cover a more comprehensive breadth of topics in relation to the systems engineering process.

Student Course Evaluations (Solicited): Course evaluations were conducted through the standard University of Michigan process, where students are asked to provide anonymous feedback on the course. To show complete growth, end-of-year quantitative data, recorded on a 5.0 Likert scale, is captured in Table 2, and qualitative comments from throughout the year are provided as well. (Because survey responses were optional, the surveys' sample sizes only covered a fraction of the course participants.)

Table 2: *Statistics from End-of-Year Student Course Evaluation Responses (n = 6)*

Dimension	Course Avg	University of Michigan Engineering Average	Course B/(W) than University of Michigan Engineering Average
This course advanced my understanding of the subject matter	**5.0**	4.5	0.5
My interest in the subject has increased because of this course	**5.0**	4.2	0.8
I knew what was expected of me in this course	**5.0**	4.4	0.6
Overall, this was an excellent course	**5.0**	4.3	0.7
I had a strong desire to take this course	**5.0**	4.1	0.9
I developed a greater understanding of my ethical responsibilities	**5.0**	5.0*	--
I developed a greater understanding of my responsibilities as a professional	**5.0**	4.5*	0.5*
This course improved my ability to communicate technical information, designs, and analyses	**5.0**	4.4*	0.6*
I developed a greater understanding of the impact of engineering on society	**5.0**	5.0*	--
I developed a greater understanding of the impact of engineering on the environment	**4.8**	4.4*	0.4*
I now have a greater understanding of the contemporary issues in this field	**4.9**	4.9*	--

Qualitative comments, from both mid- and end-of-year surveys, included:

- "This is probably the most useful course I have taken in my entire life."
- "Very good instruction, with applications to our project teams to help us understand the topics"
- "One of the best academic experiences of my life…"
- "Fantastic course, the x88 course series will be an amazing addition to the curriculum…"

External Feedback from Design Review Judges and Other Sources (Unsolicited): Multiple sources of feedback were provided by design review judges and other executives who had interactions with the course; these are presented in Listing 2.

Listing 2: *Verbatim Feedback*

- "... this new design / build / fly course is impressive. Students will get exposed to a full cycle of PDR, CDR, and FRR as well as learn elements of managing a program through product development. Exposure to risk-based decision making, FMEA, and requirements decomposition with MBSE concepts is unique for an undergraduate level course. The experience will go a long way to create true systems thinkers and to prepare students for positions in the aerospace workplace."—*Jennifer Duke, Executive Director, Pratt & Whitney*

- "This course will set a new standard."—*A. Harvey Bell, Professor of Practice, University of Michigan College of Engineering and former Powertrain Executive, General Motors Corporation*

- "… this is an outstanding course and what you put together is phenomenal. BTW I love how this course is set up as a 'full two semesters' vs trying to cram everything into 15 weeks…" —*Karen Albrecht, CEO, Karen Albrecht Enterprises and former Lockheed Martin executive*

- "(taking this course is) one of the greatest decisions I've made in college. So, from the bottom of my heart—thank you."—*Cameron Behar, Aerospace Engineering junior, and Captain of the Michigan Drone Racing team… and "liked" by over half of the class in a Slack message exchange*

Feedback Summary and Conclusions: Sources of feedback were consolidated into the following key takeaways:

- This course holds promise in fulfilling its mission of bridging the gap between employers' expectations and university performance in delivering a comprehensive systems engineering experience.
- The course gets high marks in anonymous student surveys; improvement opportunities include the planned physical lab expansion and a programming lab to help increase student scores on ability to apply math and science to engineering problems.

Forward Work

The course launched in fall, 2020 with a virtual "lab" sequence due primarily to COVID-19 and inability to secure and establish safe in-person laboratory space for physical experiments.

- Virtual labs will be enhanced via "lessons learned" and student feedback.
- If conditions allow for in-person education in fall 2021, physical labs will be established to provide a hands-on component and further reinforce the learnings. (Planning is already underway to protect for an in-person experience.)

These enhancements are summarized in Table 6, with the proposed changes emphasized in ***bold italics***. Please note that the order of labs has also been modified.

Table 6: *Lab Sequence Modifications*

Lab	Exercises Implemented to Reinforce Outcomes	
	Virtual Component	**Physical Component**
Lab 495-01: Requirements	• Create a guided requirements model • Team assignment to model team's requirements • Individually cascade requirements to subsystem-level	• ***N/A***
Lab 495-02: Computer Aided Design (CAD)	• Model a basic 2D extrusion • Model a complex propeller • Assemble propeller model with other parts	• ***3D print propeller model***
Lab 495-03: Computational Fluid Dynamics (CFD) and Finite Element Method (FEM) Simulations	• Run CFD analysis on a 3D propeller model • Generate FEM stress and displacement simulations for the propeller model	• ***N/A***
Lab 495-04: Manufacturing with Computer Numerical Control (CNC)	• ***Geometric Dimensioning & Tolerancing (GD&T)*** • ***Generate model and CNC cutter paths for an injection mold of the propeller in Lab 2*** • Create a cost-benefit analysis	• ***Demo:*** ***show how a tool/cavity (created from a clear material) fits with student-modelled propellers (die-lock)***
Lab 495-05: Multi-Domain Control Systems	• Model a multi-domain controls system • Add specifications for the system • Simulate system with specifications	• ***Build and program a basic microcontroller system to drive a test stand*** • ***Compare test stand results to Lab 3***
Lab 495-06: Programming and Software	• ***Write code to control a simple but automated system based upon feedback from sensors (no human intervention).*** • ***Learn how to validate code, and write a script to automatically validate the control code written***	• ***Run the algorithm on a physical lab bench exercise – a propeller system where students balance thrust vs. gravity. The propeller will have to achieve equilibrium on its own***

Additional enhancements to lecture material and general course delivery, also based on lessons learned captured in a shared instructor repository, and student feedback include:

- A stronger and clearer tie between lecture material and individual and team assignments
- Lab 495-04 will be streamlined to fix software bugs and allow for completion within the two-week window, even if students are working remotely
- A programming lab will be added to teach students valuable skills in software and controls
- Labs will provide increased accommodation for a variety of skill levels (i.e., allow accomplished users to experiment more, perhaps for extra credit)
- Formal lab recaps will be provided in lecture and/or recitation sessions after the labs are due
- More formal office hours and study session opportunities will be provided (partly a COVID-19 logistics issue in the inaugural offering)

Additionally, scaling will occur along several vectors:

- In fall 2021, the course aims to pick up at least three additional teams—a marine-based project, an autonomous drone team, and a new student project team which aims to build an aircraft focused on sustainability and humanitarian missions.
- Upon continued success, the course will expand into three courses, one at each the sophomore, junior, and senior levels, which will expand the learnings relative to experience level within an industrial product development environment (ref. Figure 6). Students will see gradually more sophisticated applications of the teachings as they rise through each level, potentially leading to a systems engineering leadership concentration upon graduation. Furthermore, seniors will mentor juniors, who will mentor sophomores, consistent with what currently takes place in an industrial product development setting.

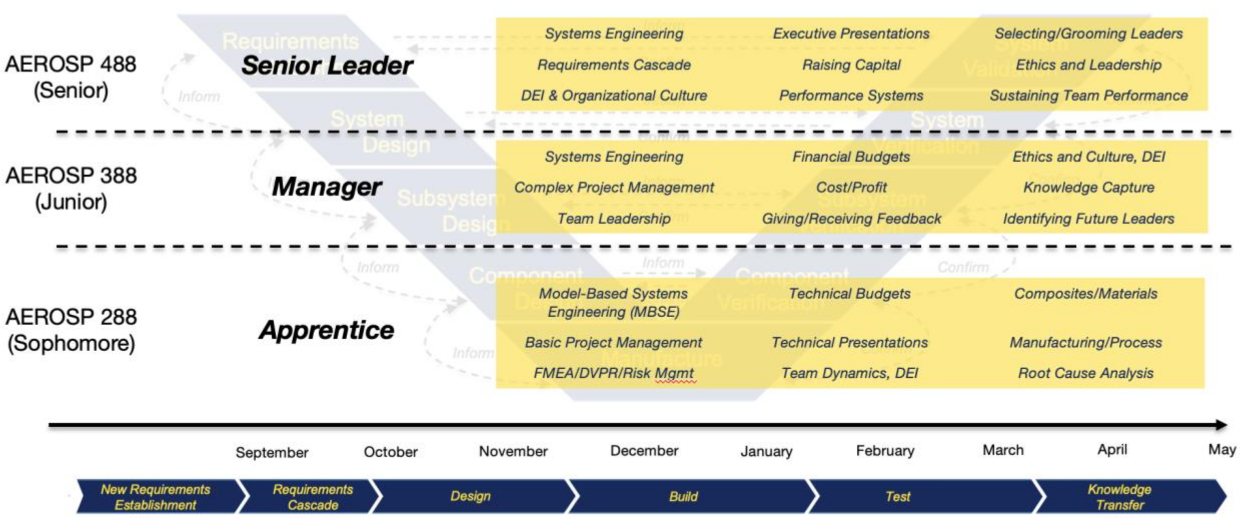

Figure 6: *Future Expansion of Systems Engineering Leadership*

- Additionally, upon continued success after the second year, the structure and teachings will be offered to other departments within the University of Michigan College of Engineering.

Scaling Challenges

Three (3) significant scaling constraints have been identified and will need to be addressed to facilitate widespread adoption of the course:

1. Student team format -- the current format relies on students being on one of dozens of student project teams in the College of Engineering (of which probably eight are in Aerospace Engineering) and take the course over two semesters. Not all students desire such an experience, and consideration will be given to developing a variant where students are given a smaller project which can perhaps be completed in a shorter period of time. (*Note as mentioned above the two-semester format has been cited as a strong positive element of the course, enabling students to not only learn the skills, but apply them in longer hands-on projects to reinforce the learnings. A balance will need to be struck between these potentially conflicting objectives*.)
2. Faculty -- current capacity in the lab space being constructed for fall, 2021 will accommodate 80 students every time the course is run, assuming a dedicated professor and capable student instructional team can be identified. Having a single professor who has other teaching responsibilities delivering the course further reduces this capacity. If this course is to be expanded, additional faculty will be required to run the course twice per year, and handle additional lab sections
3. Lab facilities -- the single lab being constructed for fall, 2021 will be sufficient to handle the second year of 495 pilot, and potentially accommodate two courses (e.g. 288 and 488) in the fall with 5 sections (50 students) each per semester. Full expansion to x88 and handling of 6-8 sections of each will require additional MBSE lab space, and likely leveraging of other aerospace engineering facilities (wind tunnels, structural testing facilities, shared computer labs, etc.).

Lessons learned throughout the year 2 pilot of 495, which will be the first in a physical lab facility, will inform the strategy and help determine how to address these three constraints.

Conclusions

The proposed Aerospace Systems Leadership course has been successfully implemented in pilot form. Feedback from students and industry partners (judges and co-collaborators) is exceptionally positive and indicates that these teachings are on the right track to integrate and cement student learnings on core subjects into a cohesive Systems Engineering experience. More importantly, students in the course understand the value of the systems engineering and essential business processes and tools, both for their current projects and for future engagements in industrial internships as well as full-time employment upon graduation.

Most of the course pedagogy received high marks for content and format; what students particularly appreciated was the thoughtful and comprehensive approach around systems, which informed the development of their aircraft and is expected to provide great benefits when they enter the workforce. In this latter vein, the course teachings resonated strongly with recruiters during students' interviews. Additional efforts to bring in "real-world" experiences such as graded design review judging, the "performance bonus" incentive, disciplined application of systems engineering and Model-Based Systems Engineering, and guest lectures from distinguished industry practitioners on essential business skills were also highly valued. Most of the improvement suggestions around streamlining the simulation lab, providing more frequent structured professor office hours and "team time" in class, and pursuing a physical lab build are being implemented for the 2021 academic year and beyond.

In summary, continued and expanded offerings of such courses is strongly recommended in order to give students a demonstrated understanding of engineering experiences post-graduation, as well as equip them with essential systems and leadership skills demanded by future employers. These offerings will be expanded at the University of Michigan—deeper in Aerospace Engineering, as well as offered more broadly across other engineering disciplines.

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