HOW CAN YOU CREATE EXPERT SYSTEMS ENGINEERS AT THE UNDERGRADUATE LEVEL?

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ANSWER: YOU CAN'T

HOWEVER, YOU CAN INSTILL BASIC PRINCIPLES OF MBSE AND SYSTEMS ENGINEERING PROCESSES TO ENSURE EVEN NEWLY-GRADUATED ENGINEERS ARE STEEPED IN SYSTEMS FUNDAMENTALS

OBJECTIVE + BRIEFING STRUCTURE

1

Share **Systems Engineering** and **MBSE** undergraduate educational efforts at the University of Michigan

2

Demonstrate advantages and **opportunities** for **industrial corporation partnerships**

3

Spark thinking on an **INCOSE certification** for undergraduate teaching – either an existing certification or a new offering

AGENDA

SYSTEMS, LEADERSHIP, & PROFESSIONALISM– CASE FOR CHANGE

MBSE Course Series Concept & Execution

- Pedagogical concept
- AEROSP 495: Two-Year Course Pilot
- x88 Pilot-Informed Course Series

Benefits of Corporate Sponsorship & Engagement

Summary, Q&A

WE ARE FALLING SHORT.

"…**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**…"

Source: R.M. Felder, D.R. Woods, J.E. Stice, and A. Rugarcia, "The Future of Engineering Education: A Vision for a New Century." Chem. Engr. Education, 34(1), 26–39 (2000) Chem. Engr. Education.

TOP SKILLS SCHOOLS DO NOT PREP STUDENTS FOR

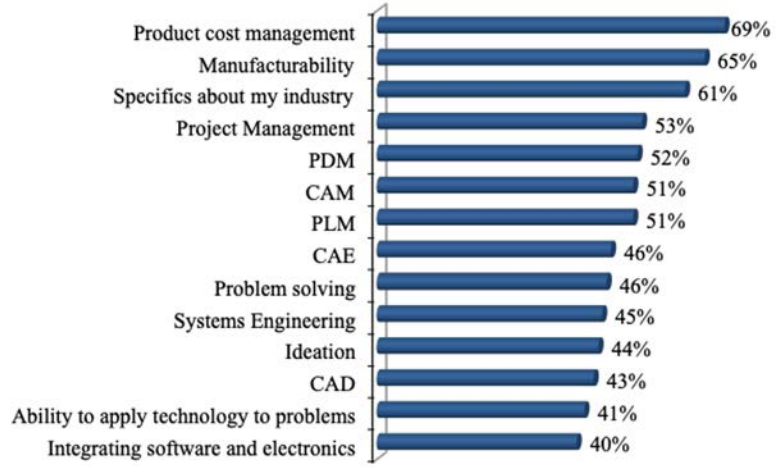

Figure 6: Top Skills Schools Do NOT Prepare Students Well

Source: M. Boucher, "Close the Engineering Skills Gap! Prepare New Graduates to be Real World Ready," Tech-Clarity, 2017. Available: https://techclarity.com/enigneering-skills-gap/8423

INSIGHT

EMPLOYERS HAVE FOR DECADES CITED KEY UNMET NEEDS IN COLLEGE ENGINEERING EDUCATION.

ACADEMIA IS FALLING SHORT.

David Taylor

VP Industry Strategy, Marketing, & Global Execution
Siemens Digital Industries Software

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Systems, Leadership, & Professionalism–
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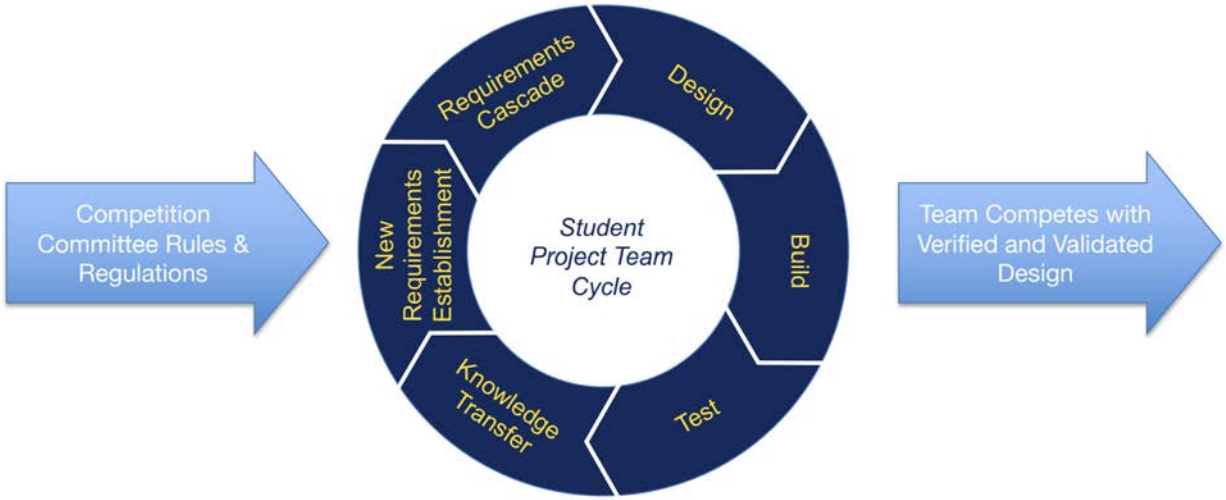
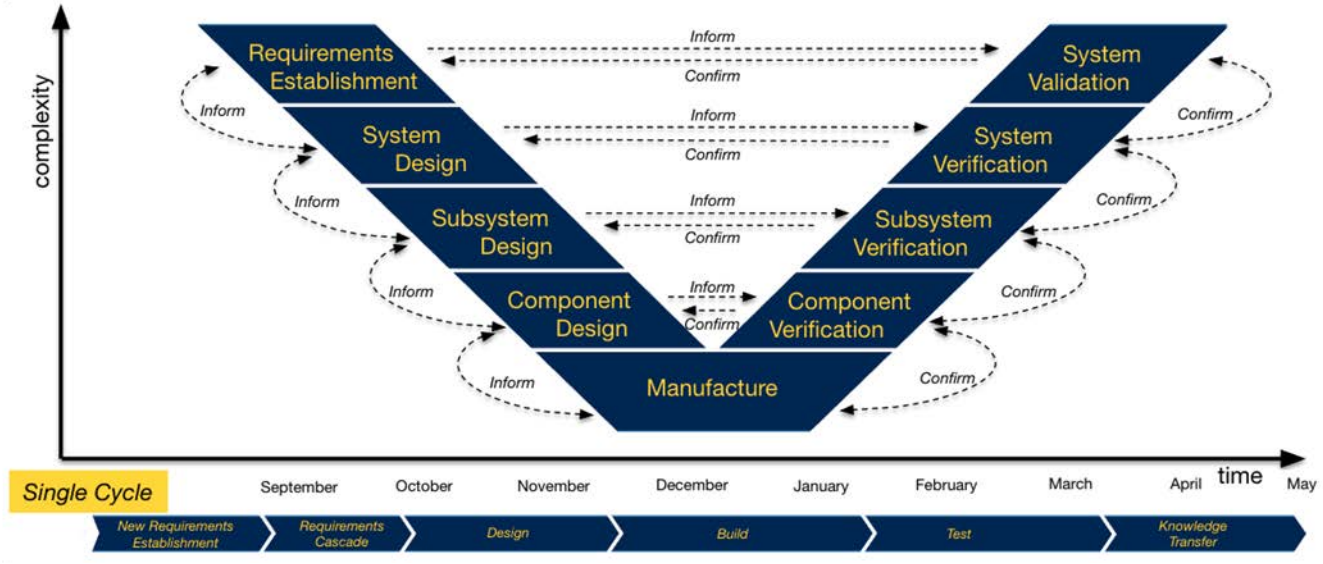
CLOSED LOOP



INSIGHT

Annual process, aligned to both academic and student project team calendar, provides framework for facilitated, hands-on, practical learning. Striking parallels to complex product development in industry.

SYSTEMS V-BASED STRUCTURE



INSIGHT AND CHALLENGE

Adopting Systems V approach to project cycle yields methodical system breakdown and disciplined rebuilding through MBSE for optimal system performance & design efficiency

How do we construct an undergraduate course series containing the key elements of this model?

APPROVAL SEQUENCE

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AEROSP x88 PILOT

Featured at:

ASEE Conference – July 2021

World Engineering Education Forum – October 2021

PDR
Judged & graded

CDR
Judged & graded

FRR
Judged & graded

AEROSP 495

Systems Engineering/MBSE	**Risk Management**	**Value Stream**
Project Management	**Verification & Validation**	**Root Cause Analysis (6σ)**
Effective Teams	**Manufacturing**	**Budgets**

Peer Reviews
Judged & graded

Peer Reviews
Judged & graded

Year 2 Pilot Class Composition:

- 2 non-aircraft teams (space cargo vessel, electric hydrofoil)
- 17 of 31 (55%) enrolled students are women or URM
- 10 of 31 (32%) enrolled students are non-Aerospace (Mechanical, Electrical, Chemical, Biomedical, Space Sciences)

MBSE Labs (Year 1)

	1. Requirements	2. CAD	3. Simulation (CFD, CAE)	4. Manufacturing	5. Multi-Domain Systems	6. Programming & Controls
Virtual (Fall 2020+)	Analyze drone example in Capella. Create testbench requirements cascade in Capella	Design propeller and shaft assembly in Siemens NX	Star-CCM+ used to calculate aero pressures. Resultant forces into NASTRAN for structural analyses	Tool cutter paths created in NX. Injection mold vs. 3D printing inflection point calculated	Model propeller, shaft, battery, & microcontroller system and perform power simulations	N/A
Physical (Fall 2021+)	N/A	N/A	N/A	N/A	N/A	N/A

Lab series modeled to provide students with an MBSE overview applied to a simple and known system. Students then applied these learnings to their systems projects.
All virtual in Year 1 due to COVID.

MBSE Labs (Year 2)

	1. Requirements	2. CAD	3. Simulation (CFD, CAE)	4. Manufacturing	5. Multi-Domain Systems	6. Programming & Controls
Virtual (Fall 2020+)	Analyze drone example in Capella. Create testbench requirements cascade in Capella	Design propeller and shaft assembly in Siemens NX	Star-CCM+ used to calculate aero pressures. Resultant forces into NASTRAN for structural analyses	Tool cutter paths created in NX. Injection mold vs. 3D printing inflection point calculated	Model propeller, shaft, battery, & microcontroller system and perform power simulations	Model controls for propeller system and program microcontroller to execute them
Physical (Fall 2021+)	N/A	Generate G-Code and 3D print propeller model	Verify forces and loading on a thrust test stand plus wind tunnel experiments	Demo die-locked part and mold-tool best practices	Build and test microcontroller and propeller system	Flash code to microcontroller and test control system

Enhanced MBSE sequence with physical laboratory exercises made possible by corporate sponsors. We also took lessons learned from the first year to improve the quality and delivery of the virtual lab portion.

Aerospace 495 Ecosystem

LOCKHEED MARTIN

GENERAL ATOMICS AERONAUTICAL

leidos

Collins Aerospace

Pratt & Whitney

AIR serv

SIEMENS

Gulfstream
A GENERAL DYNAMICS COMPANY

ROLLS ROYCE

FXB
FLIGHT VEHICLE INSTITUTE

AEROSP 495

PDR
Judged & graded

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Effective Teams	**Manufacturing**	**Budgets**

Peer Reviews
Judged & graded

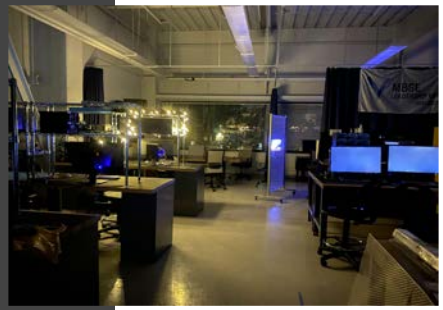
Peer Reviews
Judged & graded

Strong partnerships developing with key industry partners in many sectors – critical to educational mission.

MBSE Leadership Lab

- First-of-its-kind MBSE Leadership Lab
- Opened September 2021 for AEROSP 495 course pilot year 2
- Enables physical lab work and teaming space to supplement and validate MBSE modeling
- Key corporate sponsors include: Blue Origin, Collins Aerospace, Leidos, Pratt & Whitney, Raytheon, Siemens
- In-person unveiling event held September 9th for sponsors
- Multiple other companies have contributed in-kind
- Other companies are invited to join the partnership

MBSE Leadership Lab built in summer 2021 thanks to our generous corporate partners deeply committed to the development of the next generation of aerospace leaders.



David Taylor

VP, Industry Strategy, Marketing, & Global Execution
Siemens Digital Industries Software

AEROSPACE 495 PILOT RESULTS

3 Teams in Aerospace 495:

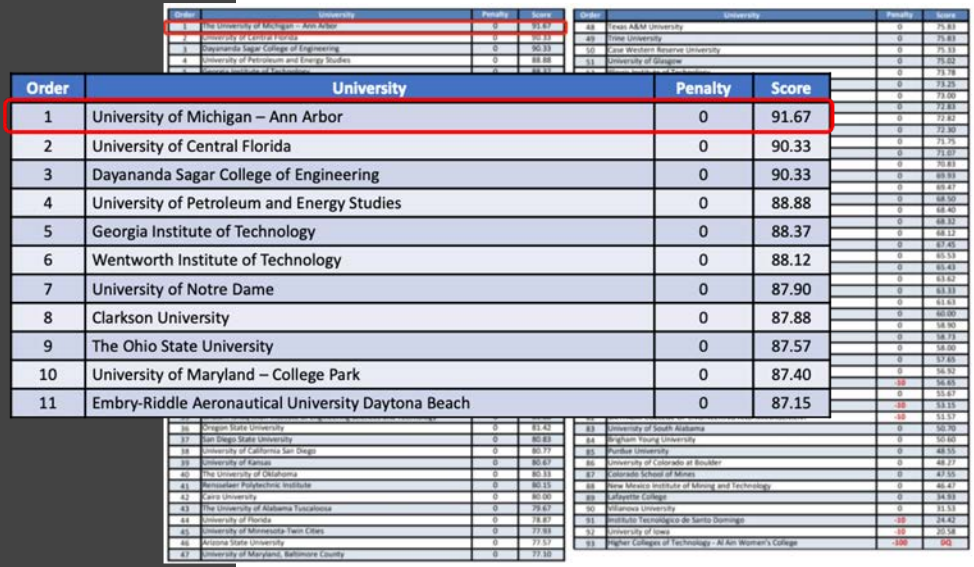
MDR - new drone racing

MACH - electric-powered twin engineer 5’ wingspan fixed wing aircraft

MVFT - eVTOL tilt-rotor autonomous aircraft

Competition Firsts (performance bonus):

1. **MVFT** - finished first in BOTH the 2021 VFS international PDR and CDR
2. **MACH** - first of 93 teams in the 2021 AIAA fixed wing international design competition



Order	University	Penalty	Score
1	University of Michigan – Ann Arbor	0	91.67
2	University of Central Florida	0	90.33
3	Dayananda Sagar College of Engineering	0	90.33
4	University of Petroleum and Energy Studies	0	88.88
5	Georgia Institute of Technology	0	88.37
6	Wentworth Institute of Technology	0	88.12
7	University of Notre Dame	0	87.90
8	Clarkson University	0	87.88
9	The Ohio State University	0	87.57
10	University of Maryland – College Park	0	87.40
11	Embry-Riddle Aeronautical University Daytona Beach	0	87.15

End-of-Year Survey (1st year)

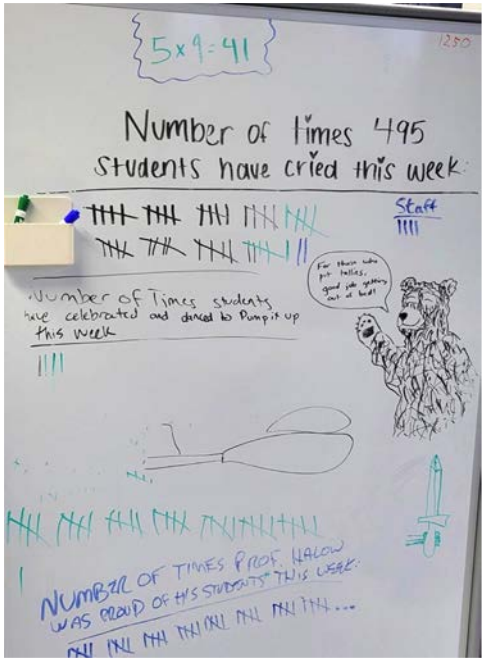
(Label)	Competency Dimension	Pre-Course Response (n = 12)	Post-Course Response (n = 12)
Quantitative Likert-Like Scale Scores (1-5)	Leadership	3.9	4.0
	Teamwork	4.0	4.4
	Risk Management	3.3	2.7
	Systems Thinking	3.7	4.4
Quantified Qualitative Responses to Open-Ended Questions (1-3)	Leadership	1.63	1.92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

Note: Risk Management scores were discussed in student focus groups and competency growth was most significant in this area.

Qualitative Score degradation was explained by students as they did not know a priori how sophisticated Risk Management was – hence the low post-course score.

- Increase between 5-10% from pre-course response
- Increase of > 10% over pre-course response
- Decrease from pre-course response

Student Experiences



Student Evaluations

Dimension	AEROSP 495
This course advanced my understanding of the subject matter	5.0
My interest in the subject has increased because of this course	5.0
I knew what was expected of me in this course	5.0
Overall, this was an excellent course	5.0
I had a strong desire to take this course	5.0
I developed a greater understanding of my ethical responsibilities	5.0
I developed a greater understanding of my responsibilities as a professional	5.0
This course improved my ability to communicate technical information, designs, and analyses	5.0
I developed a greater understanding of the impact of engineering on society	5.0
I developed a greater understanding of the impact of engineering on the environment	4.8
I now have a greater understanding of contemporary issues in this field	4.9

STUDENT VERBATIMS

"This is probably the most useful course I've taken in my entire life"

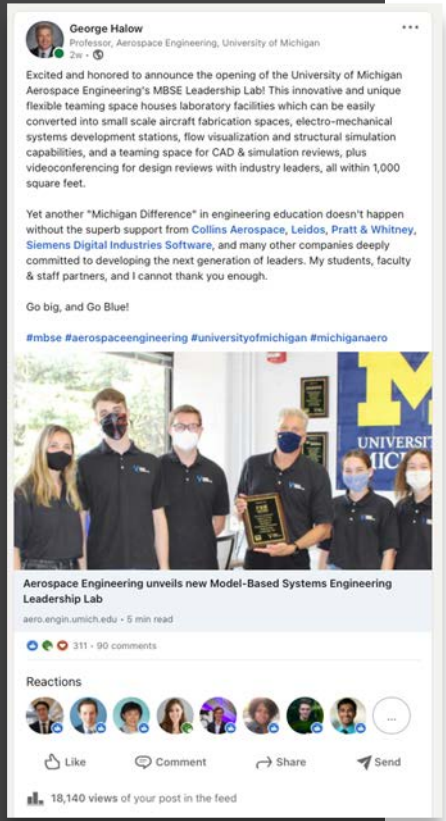
"Very good instruction, with applications to our project teams to help us understand the topics."

"One of the best academic experiences of my life…"

"Fantastic course, the x88 course series will be an amazing addition to the curriculum…"

Student Feedback
University of Michigan

Additional Feedback



"...this new design/build/fly course is a stroke of genius. Students will get exposed to a full cycle of PDR, CDR, & 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

"Impressed with new MBSE lab and plan to migrate learnings from Aero 495 to x88. A stepping stone that needs to be expanded."

- University of Michigan Industrial Advisory Board (IAB)–annual meeting on September 23/24, 2021

Arthur Mabbett

VP & Deputy Operations Manager
Leidos Innovation Center (LInC) at Leidos

Mauro Atalla

Sr. VP, Engineering & Technology
Collins Aerospace

Informing x88

POSITIVES

+ Course went from approval to prod in <6 months during the heart of the pandemic
+ Extremely well-received by students, colleagues, industry groups (ie. ASEE)
+ 2-semester format is strong from the learner and corporate perspective (although a potential inconvenience for students/co-ops) to fully assimilate product development learnings
+ Industry partners putting their money where their mouths are in terms of supporting and recruiting
    + >$500,000 raised for an **instructional** lab in 14 months
    + Further interest continues

OPPORTUNITIES

- Add a physical lab component (completed)
- Go deeper on some key topics (risk management, 6σ, manufacturing processes, leadership and transition) and add content (GD&T) – included in expansion to x88
- Integrate more technical elements of MBSE – become a true academic leader in MBSE tools as well as process (completed with hire of Prof Cinar)
- Scale to larger populations of students, and variety of projects (ref. backup)
- Add System Requirements Review (SRR) gateway to ensure robust requirements establishment and cascade to subsystems

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Case for Change

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- Pedagogical concept
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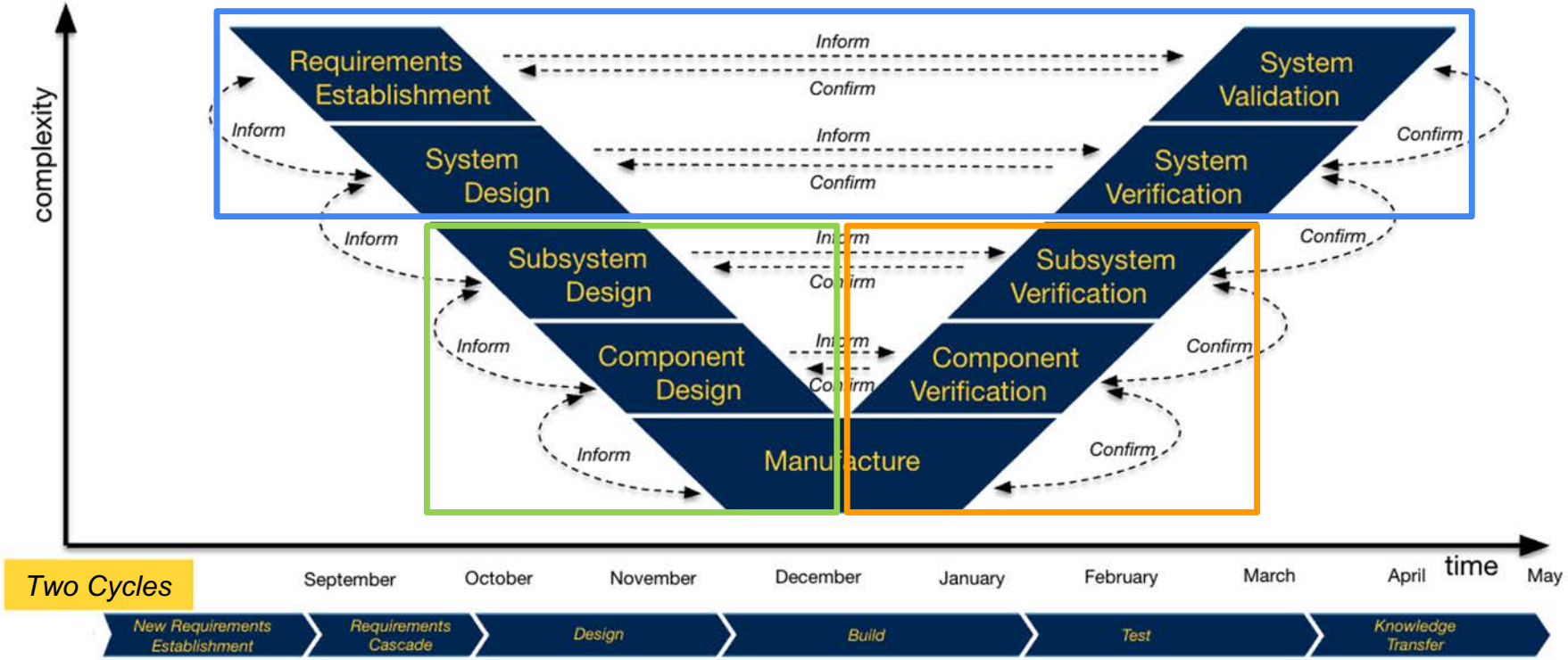
- **x88 PILOT-INFORMED COURSE SERIES**

Benefits of Corporate Sponsorship & Engagement

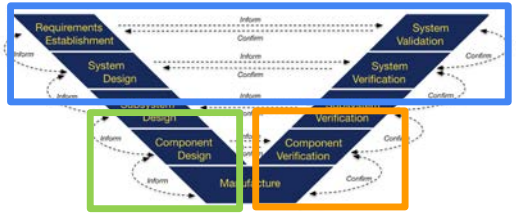
Summary, Q&A

SYSTEMS V - A Refresher



x88 COURSE OUTLINE

488 students will mentor and coach 288 and 388 students



AEROSP 488 (Jr/Sr) (4) Product Development Leadership

Systems Engineering	Financial Budgets	Ethics & Culture, DEI	Effective Executive Presentations
Complex Project Management	Cost/Profit	Knowledge Capture	Delivering at Milestones
Team Leadership	Giving/Receiving Feedback	Selecting & Grooming Future Leaders	Servant Leadership & Empathy

AEROSP 288 (Soph/Jr) (3) Fundamentals of Product Development

Model-Based Systems Engineering (MBSE)	Conducting Effective Design Reviews	Manufacturing Process/Material Selection
Basic Project Management	Technical Presentations	Geometric Dimensioning & Tolerancing (GD&T)
FMEA/DVPR/Risk Management	Team Dynamics, DEI	Technical & Cost Budgets

Intro to Quality Engineering	Statistical Modeling	6σ Root Cause Analysis Deep Dive
Physical Testing Methodologies	Model/Testing Correlations	Multi-Criteria Decision Making
Design of Experiments	Managing Product Variability	Field Validation/ Flight Testing

AEROSP 388 (Soph/Jr) (4) Aerospace Tools & Methods (MBSE)

September | **October** | **November** | **December** | **January** | **February** | **March** | **April** | **May**

New Requirements Establishment → *Requirements Cascade* → *Design* → *Build* → *Test* → *Knowledge Transfer*

MBSE Labs (x88)

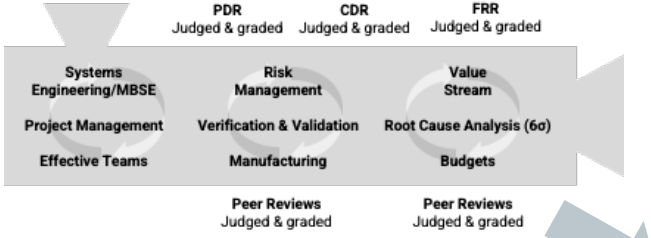
New Lab

	1. Requirements	2. CAD	3. Simulation (CFD, CAE)	4. Manufacturing	5. Statistical Modeling	6. Multi-Domain Systems	7. Programming & Controls
Virtual (Fall 2022+)	Analyze drone example in Capella. Create testbench requirements cascade in Capella	Design propeller and shaft assembly in Siemens NX	Star-CCM+ used to calculate aero pressures. Resultant forces into NASTRAN for structural analyses	Tool cutter paths created in NX. Injection mold vs. 3D printing inflection point calculated	Create design of experiments. Perform basic multivariate statistics, analysis of variance, and regressions	Model propeller, shaft, battery, & microcontroller system and perform power simulations	Model controls for propeller system and program microcontroller to execute them
Physical (Fall 2022+)	N/A	Generate G-Code and 3D print propeller model	Verify forces and loading on a thrust test stand	Demo die-locked part and mold-tool best practices	N/A	Build and test microcontroller and propeller system	Flash code to microcontroller and test control system

288 388

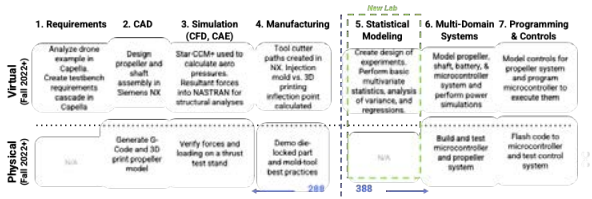
Students learn MBSE in a controlled series of experiments on a relevant system before application on their own craft. All labs except Lab 5 exist in some form today.

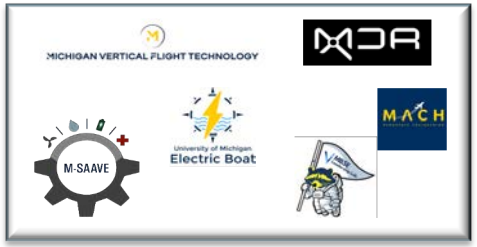
Student Projects in x88



Systems Engineering Processes

Systems Engineering Tools





- All students will participate in group projects
- Systems Engineering processes and MBSE tools taught to inform students how to execute their projects
- 488 students will take leadership roles in their project groups
- Gateway Reviews by corporate partners

Our Team - Students

Elizabeth Baubkus
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BS Aerospace Eng ‘21
MS Aerospace Eng
F/T Hire May ‘22

Fluid Mechanics, Space Vehicle Design, MBSE

Hunter Sagerer
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BS Aerospace Eng ‘23
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Internship Summer ‘22

Space Systems Engineering, MBSE

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F/T Hire May ‘22

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MS Aerospace Eng ‘24
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Structures, Aircraft Design, MBSE

Julia Weiss
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BS Aerospace Eng ‘21
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Internship Summer ‘22

Advanced Aircraft, Flight Analysis, MBSE

GSI: Graduate Student Instructor
IA: Instructional Aid

Our Team - Faculty

George Halow
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Director, Aerospace Leadership Master of Engineering Program

Gokcin Cinar
Assistant Professor,
Aerospace Eng
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Principal Investigator, Integrated Design of Environmentally-friendly Aerospace Systems (IDEAS) Lab

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BENEFITS OF CORPORATE SPONSORSHIP & ENGAGEMENT

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CORPORATE ENGAGEMENT – x88 & LAB

Participating in Student Gateway Reviews (currently evenings US Eastern time)

- SRR – mid-October
- PDR – early December
- CDR – early February
- FRR – mid-late March

Recruiting

- Student and instructional staff resume dossier established – will grant access to any recruiting personnel from partner companies; sponsors get advance access

Sponsorship

- Plaque on the “Wall of Fame”
- Early access to student resumes
- PR and advertisement
- Ability to request specific systems projects to run through the course series
- Be part of a multi-party Sponsor Working Group (SWG) to shape future versions of the course to meet sponsor and industry needs
- Joint MBSE and systems engineering research projects with other corporate sponsors

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SUMMARY, Q & A

Arthur Mabbett

VP & Deputy Operations Manager
Leidos Innovation Center (LInC) at Leidos

Mauro Atalla

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OBJECTIVES & SUMMARY

1. **Share Systems Engineering and MBSE undergraduate educational efforts at the University of Michigan**
    - Curriculum steeped in MBSE, systems engineering processes, and essential business and project management skills in developing complex products in an industrial environment
    - Covers product design, tools and methods, and systems integration
    - Deep industry involvement and partnerships are key elements separating x88 from other offerings
2. **Advantages for Industrial Partners**
    - Recruiting top students with systems engineering and MBSE training
    - PR at a top Aerospace Engineering institution (plaque on Wall-of-Fame, access to students through design reviews)
    - Co-authorship of papers and recognition in conferences and other public events
    - Ability to shape future versions of teachings through a Sponsors' Working Group (SWG)
    - Ability to run projects through the course
    - Joint research projects with other corporate sponsors
3. **Credential/Certification (INCOSE)**
    - Is there an appetite for creating and/or applying an existing INCOSE certification?

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Scaling to x88 – Challenges

TODAY'S CHALLENGES

Student team format: catering only to student project teams which follow the 9-month September – May academic calendar for their craft design/build/compete cycles is restrictive to enrollment

Faculty capacity – having a single faculty member teach all three x88 courses, plus another undergraduate course, while running a master's program

Lab facilities – single lab will be challenged at best to handle all three x88 courses if we want to push more than 50-60 students per year through the sequence

Initial approved course structure – three (3) courses each spanning a full academic year – challenging for students to fit into a full 128 credit hour curriculum; even more difficult for transfer students

DEVELOPMENTAL SOLUTIONS

- Allowing students to form teams and pick projects (subject to instructor approval), similar to other Capstone design courses
- Running the course 2x per year (September through May, and January through December) to be investigated for future

- Integrating other lab courses and instructors
- New faculty member to teach AEROSP 388
- Migration to other Engineering departments could drive a sharing of the teaching load

- Secure additional lab space or additional capital for facilities
- "Compartmentalize" course segments so lab work in alternating semesters utilizes different lab spaces (MBSE Leadership Lab, wind tunnel, other UM lab facilities)

- New x88 model allows full series to be completed in 2 vs. 3 years
- 2 of the courses bumped to 4 credit hours, and spanning a semester vs. a full academic year

Multiple levers can and will be invoked in future semesters to allow for seamless capacity expansion.