Introducing the “Entrepreneurial Mindset” into Arizona State University’s Aerospace Engineering Capstone Design

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This paper highlights efforts made at Arizona State University to infuse an “Entrepreneurial Mindset” into the Aerospace Engineering program. Because this sort of curriculum reform cannot be achieved alone in a single capstone, we discuss how our university made widespread academic-unit efforts to evangelize the need for practical, end-user focused examples in lower-level curriculum. In addition to the capstone class, we highlight efforts made in two, junior-level Aerospace Engineering classes that specifically prepare students for a Capstone that involves designing an aircraft to broad market requirements.

I. Introduction

THE Kern Family Foundation was established in 1998 by Robert D. and Patricia E. Kern, founders of Generac Power Systems of Waukesha, Wisconsin. The stated mission of the Foundation is “to empower the rising generation of Americans to build flourishing lives anchored in strong character, inspired by quality education, driven by an entrepreneurial mindset, and guided by the desire to create value for others” [1] Among its activities, the Foundation sponsors KEEN, the Kern Entrepreneurial Engineering Network. KEEN funds select universities to develop curriculum to further the foundation’s broad goals to ensure that engineering school graduates can create “personal, economic, and societal value through a lifetime of meaningful work;” see FIGURE 1. [2]

Arizona State University (ASU) is one of three universities governed by the Arizona Board of Regents; see FIGURE 2. [3] ASU is an “R1” classified research university, offering a wide range of more than 350 undergraduate and 400 post-graduate degree and certificate programs across many disciplines including the arts, sciences, medicine, law and engineering. [3] Today, ASU enrolls approximately 150,000 students between its five campuses and on-line programs. [4] At the Tempe campus, where we work, we have more than 55,000 students attending. Our academic unit, the Fulton Schools of Engineering (FSE), has an active presence on two campuses educating over 20,000 undergraduates. In 2021, co-author Takahashi’s program, the Aerospace Engineering program, enrolled 925 undergraduate students. It is one of the largest enrollments in the Southwest. [5] In the course of a typical academic year, Takahashi’s capstone (the Aeronautics degree track) touches 60 to 65 students.

FIGURE 1 – Engineering Unleashed website hosted by the Kern Entrepreneurial Engineering Network (KEEN).

FIGURE 2 – Arizona State University

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This paper documents Arizona State University's efforts to incorporate "Entrepreneurial Mindset" goals into its Aerospace Engineering – Aeronautics capstone class.

II. The KEEN Grant at Arizona State University

The Kern Family Foundation awarded a grant to the Ira A. Fulton Schools of Engineering (FSE) at Arizona State University (ASU) to integrate Entrepreneurial Mindset (EM) concepts and practices throughout the undergraduate curriculum. The grant supported mentorship of engineering faculty in building a "community of practice," and directly funded curricular reform to weave Entrepreneurial Mindset (EM) into three required courses in each of FSE's 18, ABET-accredited programs. EM-focus courses in each program were first-year introduction to engineering, one required technical course at the sophomore or junior level, and Capstone. [7] Co-author Lichtenstein, Co-PI of the grant, sat on the leadership team as Director of EM@FSE Program Effectiveness. Co-Author Takahashi directly participated in the "community of practice," which sought to facilitate engineering faculty professional success utilizing EM-based mentorship and offered workshops and one-on-one faculty mentoring to develop and integrate EM into the existing ABET accredited curriculum. As the Aeronautics-Track Professor-of-Practice, it was Professor Takahashi's duty to integrate EM into any introductory, sophomore and junior classes he taught so that students in the EM-focused capstone course would have prior experience integrating curiosity, making connections, and creating value into their projects.

In a 2007 interview with the *Milwaukee Journal Sentinel*, Kern, who has a mechanical engineering degree from the University of Illinois, said "there's a gross shortage of engineering talent in this country." [8] We believe that a functional engineer must have an ability to design (rather than simply analyze). We also believe that design encompasses more than just CAD skills. Design involves engineers helping develop requirements in addition to our usual tasks as analysts or manufacturers. A well-structured design process encourages students to think more broadly about the world around them and understand the customer who they are designing for. The KEEN Framework, developed over the past decade (long before ASU's association with the Kern Family Foundation) outlines targeted educational outcomes for opportunity skills; this helps focus faculty to include specific course objectives that reinforce the development of an entrepreneurial mindset. These objectives include a need to communicate a proposed engineering solution in economic value, market interest, and societal benefit.

The KEEN Framework defines the Entrepreneurial Mindset in terms of "the 3 C's:" **constant curiosity** and **making connections** in order to **create value**; see FIGURE 3. [9] The idea here is that engineers find success and personal fulfillment when they couple their skills with a mindset that focuses their talents to create extraordinary value for others. KEEN's vision is that broadly curious engineers can understand the world, look towards the future and understand how to explore multiple perspectives. Since large projects, such as an aerospace system design, span more skill sets than any one engineer can master, engineers need to make connections across a diverse peer group, academic disciplines, and real-world applications to invent new approaches to complex problems. Together, this connected team can think "outside the box" "place old ideas in new contexts" and gain insight. Finally, a complete design expresses a harmony between desire and reason – a technically proficient machine that fulfills a need in the broad marketplace creates value from raw potential.

FIGURE 3 – KEEN Framework Goals

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III.Developing Entrepreneurial Mindset Objectives within the context of an ABET Accredited Capstone Class

Lichtenstein & Collofello note that abstractions (concepts) cannot be institutionalized: "…what is institutionalized are a collection of policies and practices, including syllabi and processes for documenting outcomes. [7] In order to institutionalize Entrepreneurial Mindset (EM) at Arizona State University's (ASU) Fulton Schools of Engineering (FSE), the Vice Dean for Academic and Student Affairs led an effort the produce a) the EM@FSE framework, b) Course Planning and Program Coverage documents, and c) EM@FSE Proficiency tracking. Each is discussed below.

A. The EM@FSE Framework

The first step in operationalizing entrepreneurial mindset was to devise a framework that elaborated behavioral outcomes, just as ABET student criteria do. [10]. The ASU KEEN grant core-team adapted a set of 17 indicators of entrepreneurial mindset competencies that had been previously identified by an ASU team working on an EM assessment. [11] The indicators operationalize EM qualities such as recognizing opportunity (*a, e, i, k*), customer discovery (*f, h, n*), developing an innovation (*b, c, d, g, h*), professional communication (*j, m, n, p*), lifelong learning (*o, q*) and ethics (*q*). Indicators were behaviorally orientated to facilitate classroom assessment and promote active learning, including hands-on exercises and projects. The EM@FSE indicators were mapped onto ABET student criteria in order to clarify to faculty that teaching the EM competencies is an incremental, as opposed to fundamental, shift that aligns with ABET outcomes; see FIGURE 4. Linking the initiative to ABET was intended to increase faculty buy-in and sustainability. [7]

The EM@FSE Framework: EM@FSE + ABET=ABET^{+EM}

ABET^{+EM} 1	ABET^{+EM} 2	ABET^{+EM} 3	ABET^{+EM} 4	ABET^{+EM} 5	ABET^{+EM} 6	ABET^{+EM} 7
Critically observes surroundings to recognize opportunities and apply engineering principles, technical skills, science, and mathematics to solve complex engineering problems.	Can apply human-centered design principles to discover users' needs, values propositions, and market opportunities to meet specified needs with consideration of public health, safety, and welfare as well as global, cultural, social, environmental, and economic factors. Explores multiple solution paths, suspending judgment on new ideas.	Can communicate effectively with diverse audiences, articulating how a discovery adds value from multiple perspectives.	Can recognize an engineer's ethical and professional responsibilities, understanding that potential solutions have the potential to lead to both gains and losses. Understanding how elements of an ecosystem are connected, can make informed judgements about expected and unanticipated impacts of engineering solutions in global, economic, environmental, and societal contexts.	Can function effectively on teams whose members have diverse and complimentary skillsets, backgrounds, and expertise, creating an inclusive environment characterized by shared leadership to successfully establish goals, plan tasks, and meet objectives.	Can develop and conduct appropriate experimentation and analyze and interpret data to support and refute ideas. Can conduct feedback and data from customers and/or customer segments and use engineering judgment to draw conclusions to modify an innovation accordingly.	Can seek and apply new knowledge, synthesizing information from a range of sources and/or modalities to discern trends about the changing world and adopting a future-focused perspective to assess the sustainability and/or scalability of potential solutions.

EM@FSE Indicators are shown in maroon font.

FIGURE 4 – EM@FSE tailored to ABET goals.

B. Course Planning and Program Coverage Documents

Faculty teaching the required first-year course, a required Sophomore or Junior technical course, and Capstone completed course Planning Documents. This document identified which EM@FSE objectives would be covered in the course and in which assignment(s) they could be *introduced, developed*, or *assessed*. Course Planning Documents were parlayed into Program Coverage documents that mapped the extent of coverage each EM@FSE indicator across all EM-focus courses in each ABET-accredited program. In the first year, 86% of faculty who taught an EM-focused

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course completed Course Planning documents and 94% prepared Program Coverage documents. FIGURE 5 shows the course planning document developed by co-author Takahashi for his Junior technical course, AEE 344.

EM@FSE 2.0 COURSE PLANNING DOC							Under each indicator, note whether coverage is Introduced (1), Skills Developed (2), and/or Assessed (3)										
Name of Assignment/Activity/ Assessment	a) Critically observes surround-ings to recognize opportun-ity	b) Explores multiple solution paths	c) Gathers data to support and refute ideas	d) Suspends initial judge-ment on new ideas	e) Observes trends about the changing world with a future-focused orienta-tion/ perspec-tive.	f) Collects feedback and data from many customers and customer segments.	g) Applies technical skills/ knowledge to the develop-ment of a technology /product	h) Modifies an idea/ product based on feedback.	i) Focuses on under-standing the value propositi on of a discovery	j) Describes how a discovery could be scaled and/or sustained, using elements such as revenue streams, key partners, costs, and key resources.	k) Defines a market and market oppor-tunities	l) Engages in actions with the understand-ing that they have the potential to lead to both gains and losses.	m) Articulates the idea to diverse audiences.	n) Persuades why a discovery adds value from multiple perspectives (technolog-ical, societal, financial, environment-al, etc.).	o) Under-stands how elements of an eco-system are connect-ed.	p) Identifies and works with individuals with comple-mentary skill sets, expertise, etc	q) Integrates/ synthesizes different kinds of knowledge
EM Mindset Overview	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
HW # 1- Understanding CFR Requirements															2,3		2,3
HW # 2 - Understanding Operational Requirments			2,3		2,3	2,3					2,3						
HW # 3- Flight Mechanics & Operational Envelopes (weather, etc)			2,3			2,3					2,3						
HW # 4 - Weight Estimations		2,3	2,3											2,3	2,3		
HW # 5 - Full Configuration Drag		2,3	2,3									2,3					
HW # 6 - Running and Using EDET			2,3												2,3		
HW # 7 - Using Flight Manuals to Dispatch Aircraft			2,3														
HW # 8 - Enroute Performance Hand Calcs			2,3												2,3		
HW # 9 - Running and Using MISSION CODE Simulations			2,3												2,3		
HW # 10 - Takeoff and Landing Performance			2,3												2,3		
Project # 1 - Plotting and Interpreting Propulsion Data			2,3										2,3		2,3		
Project # 2 - Point Performance Tool Construction & Utilization			2,3										2,3		2,3		
Project # 3 - Global Airline Operations Study (Payload/Range/Runways)	2,3		2,3	2,3					2,3		2,3		2,3		2,3		2,3

FIGURE 5 – Mapping EM@FSE themes onto individual assignments and projects in AEE 344 – the 3rd year required Aircraft Performance & Sizing Class

C. *EM@FSE Proficiency Tracking*

Co-author Lichtenstein and others on the EM@FSE leadership team concurred with Gibbs [12], who argues that "assessment is the most powerful lever teachers have to influence the way students respond to courses and behave as learners." To ensure that EM was not only taught but also assessed, faculty were asked to upload aggregated student scores on each indicator assessed. The FSE class-level, target proficiency was 70% on each indicator. Prior to tracking EM@FSE indicators, presentation in EM-focus courses was often haphazard. Tracking assessment results promoted integration of EM@FSE indicators into course assignments and projects and usually resulted in EM-related material becoming some proportion of students' grades, giving heft to the initiative. Extensive support by Lichtenstein and others helped faculty learn to assess EM indicators efficiently and effectively, minimizing the time and effort required to grade student work and aggregate results to the class level. Averaged class-level proficiency was posted for each instance of EM@FSE assessment. In the first year, 69% of EM-focus faculty completed EM@FSE Proficiency tracking.

Although faculty were encouraged to integrate EM@FSE indicators in their courses, doing so was not required. Yet, as shown above, there was remarkable buy-in, even during the first year of implementation. This was in spite of significant competing priorities, including dramatic instructional obstacles due to COVID-19, and preparation of

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ABET self-studies for an upcoming accreditation renewal. We cite four reasons that uptake of the initiative was so effective early in the initiative.

1. *Foundation was laid in earlier years.* The Kern Foundation funded ASU with two prior grants before the institutionalization grant in 2020. By Fall 2020, most faculty involved had at least a passing awareness or understanding of the EM initiative. Some had already attended local EM professional development, and some faculty had taken national-level trainings and/or attended annual KEEN Network conferences. The EM@FSE framework was developed during the second grant, so implementing measures to institutionalize EM in the curriculum was understood to be an incremental advancement of the initiative. By the time the Institutionalization grant was awarded, there were clusters of faculty who had already adopted EM practices, as well as a critical mass of faculty willing to explore EM in their classes.

2. *EM@FSE Aligned with ABET.* The 17 EM@FSE indicators were intentionally aligned with ABET outcomes (refer back to FIGURE 4). Aligning EM@FSE with ABET student criteria meant that documenting EM@FSE implementation followed procedures already familiar to faculty. Also, EM@FSE addressed a pain point for many faculty—how to teach, assess, and document professional skills for ABET. Teaching and assessing the behaviorally-oriented EM@FSE indicators eased the burden many faculty faced to successfully address ABET professional skills in their courses.

3. *Incentivized Departmental Thought Leaders*. A faculty member from each ABET-accredited department was asked to participate as a Robust EM Leader (REML). REMLs had more responsibility than other EM-focus faculty and received a stipend. REMLs were asked to work with other faculty in their ABET programs. Some REMLs were more active than others. But having a critical mass of EM@FSE champions who worked closely with colleagues in their departments helped EM@FSE leadership identify programs and procedures within each program that needed extra attention. This increased faculty participation and buy-in.

4. *Excellent Professional Development Experiences*. Most EM-Focus faculty greatly valued the opportunities to interact with colleagues in workshops, meetings, and communities of practice sessions, as well as to receive the one-on-one professional development support from Lichtenstein and others. When faculty experienced greater student engagement in course material due to hands-on instruction promoted through the EM@FSE initiative, they were motivated to increase their involvement in the initiative. Exit surveys showed a strong and significant correlation between faculty members' exposure to and experience with EM@FSE and the value of EM@FSE to their teaching ($r=.56$, $p<.05$).

The EM@FSE initiative gained excellent traction during the 2020-21 year. Participation in the initiative alleviated common faculty pain points related to wanting more collegial interaction, valuable professional development, and methods for effectively teaching professional skills. In the sections below, we illustrate how Professor Takahashi integrated EM@FSE into his Aerospace Engineering courses and capstone project.

IV. Implementing Entrepreneurial Mindset Objectives into Aeronautics Capstone

A. BACKGROUND

At Arizona State University, the Aeronautics track "design spine" in Aerospace Engineering beyond freshman year largely relies upon courses taught by co-author Professor Takahashi; see FIGURE 6. All freshmen engineering students enroll in a first-year "design/build" course, titled FSE 100 where they are introduced to basic entrepreneurial mindset concepts, decision making skills, basic mechanical and electrical fabrication, and micro-controller (i.e. Arduino) programming.[13] Second semester Junior year, students take AEE 344, the introductory aircraft performance & sizing class. [14] Either concurrent

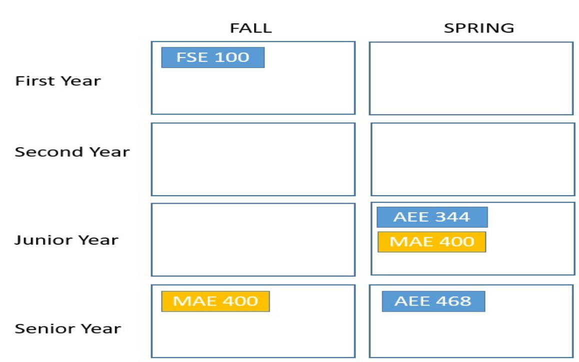

FIGURE 6 – ASU Aerospace Engineering – Aeronautics Track Major Map

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with AEE 344 or first semester Senior year, Aerospace Engineering Aeronautics track students will take MAE 400, an ethics and systems engineering class. [15] In their final semester senior year, graduating students will enroll in AEE 468, the Aircraft Systems Design Capstone course. [16] At Arizona State University, Aeronautics capstone is taught as a "paper-study" project with no physical hardware deliverables. Thus, capstone designs must be conceived and refined solely through Modelling & Simulation. Co-author Takahashi, with an extensive industrial background in applied Multi-Disciplinary-Optimization (MDO), fully embrace the Model-Based-Systems-Engineering (MBSE) approach to design. [17][18]

In order to prepare students for capstone with enhanced EM themes, Professor Takahashi made a number of changes to the two required junior year courses that he teaches.

B. E-M revision to the Required Junior Year Systems Engineering Course

MAE 400 is designed to prepare students for capstone while focusing on general business and engineering ethics, as well as covering the fundamentals of Systems Engineering. [14] All sections of MAE 400 feature a final project for which student "buddy-teams" develop a top-level business plan (including management, technical and financial elements) for engineering development. Professor Takahashi refined the business plan project to specifically utilize EM@FSE vocabulary in terms of strategic goals. Since the MAE 400 project is basically a proposal for funding future work, he ensured that the harmonized management / technical / financial plan must clearly incorporate some sort of customer market survey to help the team refine their basic concept.

The EM@FSE revised MAE 400 business plan project is conceived to represent a funding solicitation for work which has only completed the first two steps in the classic Systems Engineering "Vee," see FIGURE 7.[19] The project requires students to complete a basic feasibility study and definition of a concept of operations for a proposed future transportation product and then propose funded future development. If the proposal were to be funded, then students would be expected to execute to their advertised management / technical / financial plan.

It is in the details of the management / technical / financial plan that students actively engage in three major EM@FSE goals. For example, to develop a credible technical plan, students need to practice EM@FSE(g): "apply technical skills and knowledge to the development of a technology product." Since the technical plan is written from the perspective of funding development activities, it needs to consider EM@FSE(j): how the new product could be "scaled and/or sustained, using elements such as revenue streams, key partners, costs, and key resources." Thus students need to establish a work breakdown structure (see FIGURE 8) and propose a process whereby the final design and supply-chain can be established post contract award.[20] Since the high-level design is known to be immature, the detailed design development process must contain enough flexibility to finalize the system specification in the future. Thus, the need to plan for future trade studies based on a future finalized requirements set ensures that students plan to modify their proposed idea/ product based on feedback.

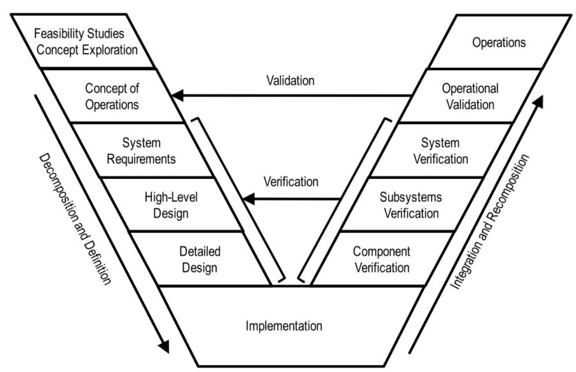

FIGURE 7– Systems Engineering "Vee" [19]

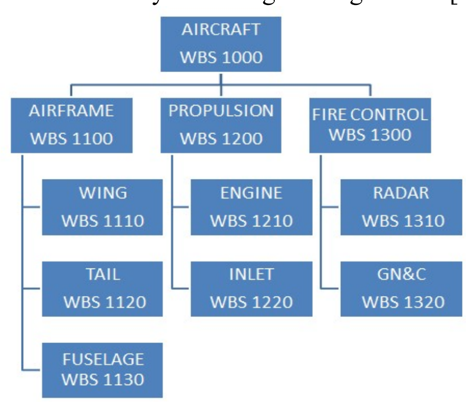

FIGURE 8 – MIL-STD 881 inspired Work Breakdown Structure; a WBS is an "org chart" of principal elements and subsystems that comprise a working system. [20]

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C. E-M revision to the Required Junior Year Aircraft Performance Course

AEE 344 is the first aviation specific course Aerospace Engineering – Aeronautics track students take. While the syllabus expects students to have a mastery of fluid mechanics and fundamental aerodynamics, it expects no prior background in aviation nomenclature, piloting experience or air traffic management; please return to FIGURE 5 to examine the EM@FSE course planning document developed for this class to see how the various individual homework assignments and three-student "buddy-team" projects cover the gamut of Entrepreneurial Mindset goals in terms of content and assessment.

AEE 344 begins with introducing students to the Code of Federal Regulations (CFR), specifically the Federal Aviation Regulations (FAR). [21] With homework that has students learn how to read and interpret the Code of Federal Regulations, they see how interconnected aviation is (the CFR covers everything from design factors of safety, materials certification basis, basic flight procedures, fuel reserves, required on-board equipment, weather reporting basis for dispatch as well as crew duty-time; it even prohibits transportation of Marijuana). In writing essay questions, students address EM@FSE(q) when they must integrate and synthesize a response based on a diverse collection of requirements.

Next, to have students gain a practical understanding of these Operational Requirements, here Professor Takahashi requires students to interrogate various aviation websites to acquire data representing the actual and equivalent-still-air distances (ESAD) between various city pairs that commercial aircraft fly. They must also identify the available runway lengths at various airports. Students address EM@FSE(c) as they write their required essay on what the general design specifications of aircraft must be to permit "legal" operation into a collection of commercial airports. To write this essay, every student must gather data to support ideas and understand how customers (i.e. airlines) address transportation needs in the commercial marketplace.

Students need familiarity with working problems fundamental to aircraft performance that consider regulatory, procedural, and operational limits as well as payload. In Homework #4, students work problems involving Flight Mechanics and Aircraft Operational Envelopes (i.e. weather). In Homework #7, students use flight manual charts to plan aircraft dispatch. Considering realistic constraints (i.e. certification limits at ISA+40ºC), students discover why Phoenix Sky Harbor airport must cancel many flights when ground temperatures exceed 117ºF. Students address EM@FSE(c)(f) and (k) when they collect enough diverse data in the numeric portion of these assignments to write an essay on market effectiveness of a given aircraft (with known payload / range and operating limit characteristics).

The Weight Estimation homework introduces trade studies and the need to explore multiple solution paths and reinforces the maxim that "everything effects everything in aviation." Here students estimate weights of aircraft (structural) as well as operational - involving a real aircraft flown over a typical day. By performing a design trade study showing how structural weight varies with wing span, students can understand that features that promote aerodynamic efficiency (extremely high span wings) might prove counterproductive at the airline level (the wings are so heavy to actually increase fuel consumption and/or reduce the economic payload); this teaches EM@FSE(l): that design choices "have the potential to lead to both gains and/or losses."

The Full Configuration Drag homework requires students to perform "hand calculations" of lift and drag based upon geometry and common "empirical" equations. A flap deflection study, where students compute stall speed as well as drag coefficient as a function of takeoff/landing flap deployment and deflection, with accompanying short essay provides further opportunity for students to reflect once again on EM@FSE(l): how a design feature has the potential to lead to both gains and losses. Here, they see that flap deployment increases *CLmax* and hence reduces the stall speed and other takeoff and landing cue speeds, but only with the expense of added drag that hurts climb.

Further homework assignments have student learn to run and use EDET, a classic NASA computer program to estimate lift and drag. [22] They also must learn to run the MISSION CODE, a pilot-style aircraft performance tool. In addition to running the codes, students must plot data and interpret results. Both of these general-purpose codes will be used heavily in Capstone design, so getting students familiar with "technician" use of "legacy" tools is key outcome.

"Buddy-team" projects introduce students to the Microsoft VBA programming language so that they can produce new tools suitable for both immediate class needs that are also re-used in Capstone. Each of these projects requires

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submission of a more formal report, addressing EM@FSE(m) when they "articulate ideas to diverse audiences." These projects require students to document both their coding process, test-case results and interpret trade-studies in a manner suitable for review by a hypothetical industry sponsor.

In each of these projects, the student teams must write essays comparing and contrasting different data sets where they see how design choices (e.g. engine size and bypass-ratio selection) express themselves. The tools develop standard-format charts of engineering parameters (i.e. a "power-hook" where thrust and thrust-specific-fuel-consumption are cross-plotted for various speeds and altitude). Some of the essays consider how design choices as well as operational use strategies impacts system level performance; these are based on "how it looks" and "how you use it" data collected by students exercising their newly developed tools. Once again, these projects touch upon multiple EM@FSE goals: EM@FSE(c) "gather data to support or refute ideas," EM@FSE(o) "understand how elements of an ecosystem are connected."

The first project has students write a general-purpose tool to parse a standard propulsion flat file of "five-column data;" that is thrust and thrust-specific-fuel-consumption as a function of speed, altitude and "power-lever-angle" setting.

This much more complex second project, has students create and utilize a Point Performance Tool; this code requires students to re-use substantial portions of the MISSION CODE (source provided) to develop and present aircraft performance data in terms of speed / altitude envelopes. [23]

The final buddy-team project is a global airlines operational study where each student team gets an aircraft type and global airline (i.e. American Airlines and B737-700, United Express and their EMB-170 regional jets or Emirates and their A380-800 fleet) and documents how the selected aircraft fits the airlines route network from a payload (seats and/or cargo), a range (between city pairs) and runway compatibility perspective (i.e. an aircraft that needs 10,000-ft to takeoff cannot operate out of an airport with shorter runways – i.e. New York's LaGuardia with ~7,000-ft runways). These essays focus deeper into the operational decision-making customers make when sponsoring a new aircraft design or making a new fleet acquisition. [24] This project really stresses EM@FSE(i) "understanding value propositions" and EM@FSE(k) "defining market and market opportunities."

D. E-M revision to Capstone Design

With refinement of these two existing classes, students are acclimatized to Entrepreneurial Mindset concepts needed for capstone throughout their junior year. Taken together, AEE 344 and MAE 400 cover all of the EM@FSE goals. MAE 400 covers the systems engineering heavy "paperwork" side where project plans require engineers to actively participate in the customer discovery process. AEE 344 covers aeronautics industry specific nomenclature, approaches and regulatory expectations. Further, AEE 344 homework and projects always have numerical "technician" tactical elements as well as essay based "business perspective" strategic elements. These projects highlight the need for engineers to produce quality numerical data to support informed decision making. With this sort of hands-on experience, students have been prepared for capstone.

As noted previously, the Aircraft Systems Design Capstone at Arizona State University is taught as a "paper-study" project with no physical hardware deliverables. Professor Takahashi has taught this class since his arrival at ASU in the Fall of 2012. As originally conceived, it was a Modeling & Simulation heavy class based upon traditional precepts in aircraft design; that the design team would be "spoon-fed" specific requirements in terms of passenger and cargo capability, speed, range and runway capability. After considering KEEN Entrepreneurial Mindset goals, the class was re-configured to make a student prepared market study an essential part of the class; thus, atypical for an aeronautics capstone, students derive customer requirements that they must reconcile with both the flight sciences and the need to comply with expected regulatory standards.

To begin, on the first day of capstone during the syllabus overview students are shown the EM@FSE guidelines tailored into "plain English" that provide strategic guidance; see FIGURE 9, overleaf. [28] Students know from the outset that they must consider and formalize requirements so that their new airplane has both societal and commercial value. They are expected to be able to perform a market survey in order to come up with competitive requirements for their new product and then design their airplane to meet these requirements. To do so, they will build numerical models

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The FSE Engineer critically **observes surroundings** to recognize opportunities and apply engineering principles, technical skills, science, and mathematics to **solve** complex engineering problems.

- Recognizing opportunity begins with being aware of what's going on around you, noticing what is so common that we don't even think about it as well as what's strange within the ordinary.
- You will apply your technical skills and knowledge to the development of a technological product

You need to consider how your new airplane has societal and commercial value!

You will come up with competitive requirements for your new product

You design your airplane to meet these requirements!

a

The FSE Engineer can apply human-centered design principles to discover users' needs, value propositions and market opportunities, to meet specified needs with consideration of public health, safety, and welfare, and/or global, cultural, social, environmental, and economic factors.

- Identify your market niche – come up with a **value proposition** for potential buyers, users, and/or decision-makers
- Explore multiple solution paths, suspending judgement on new ideas.
  - Keep an open mind when considering potential design solutions, neither discounting seemingly outlandish ideas nor embracing the most obvious ones.
  - Decide on your final design as possible, so that more design choices are based on fact, rather than speculation.
- Focus on "optimality" as well as "feasibility" - ask "should we build it?" rather than "can we build it?"

You need to formalize requirements so that your new airplane has value!

You will build numerical models to let you consider thousands of possible designs along the way!

You will design your airplane to meet these requirements!

b

The FSE Engineer can communicate effectively with diverse audiences, articulating how a discovery adds value from multiple perspectives (e.g., technological, societal, environmental, etc.).

- Be able to articulate your ideas to diverse audiences (outside panelists)
  - "Articulates" can refer to communication in writing, speaking, videos, social media, etc.
  - "Diverse audiences" can refer to engineers from multiple disciplines, laypeople of all ages and levels of education, a range of professionals (CEOs, CFOs, Chief Engineers, lawyers, etc.),
- To persuade people why your new design adds value from multiple perspectives (technological, societal, financial, environmental, etc.). The FSE Engineer analyzes the impacts and value of an innovation to society, communities, the environment, and other relevant areas and conveys that impact and value with data.

You need to make written and oral briefings to a wide audience

You will give your milestone reviews to a panel of MS students and working engineers!

Best written reports submitted to AIAA for presentation at an international conference!

c

The FSE Engineer can recognize an engineer's ethical and professional responsibilities, understanding that potential solutions have the potential to lead to both gains and losses.

- You need to understanding how elements of an ecosystem are connected,
- You must make informed judgements about expected and unanticipated impacts of engineering solutions in global, economic, environmental, and societal contexts.

You need to make some serious design decisions during 468.

You will see that extremely high-altitude flight may offer fuel burn savings but at some additional risk in the event of cabin depressurization

d

The FSE Engineer can function effectively on teams whose members have diverse and complimentary skillsets, backgrounds, and/or expertise, creating an inclusive environment characterized by shared leadership to successfully establish goals, plan tasks, and meet objectives.

The FSE Engineer can discern colleagues' strengths and leverage those strengths into work plans to complete projects on time and with high quality

AEE 468 is a buddy team project class!

Like "real world engineering" AEE 468 projects are too complex to do alone

Leverage MAE 400 - managing and coordinating work

Dr. T will serve as team mediator in case of Emergency

e

The FSE Engineer can develop and conduct appropriate experimentation and analyze and interpret data to support and refute ideas.

- Can obtain data from customers and/or customer segments and use engineering judgment to draw conclusions to modify an innovation accordingly.
- Gathers data to support and refute ideas and design decisions
- Modifies an idea/product based on feedback.

The FSE Engineer ensures that an innovation fulfills a need and value proposition by iterating accordingly.

You need to perform a market survey to establish "real world" requirements

Do not "cartoon" your final design

Use numerical models where appropriate to support your decision making

Perform many trade studies along the way to finalizing your design

f

The FSE Engineer can synthesize information from a range of sources and/or modalities to discern trends

- Be sure to develop data from different engineering disciplines, as well as from quantitative and qualitative sources
- Ask yourself "What's next?", seeking new approaches to existing solutions, or new solutions to existing problems.
- Be sure to describe how your design be scaled and/or sustained, using elements such as revenue streams, key partners, costs, and key resources.

Do not "cartoon" your final design

Your numerical models must cover many disciplines: aero, performance, weights, stability & control, safety, operating economics, etc.

Leave no stone unturned…

Consider different viewpoints

g

FIGURE 9–ABET+EM Outcomes mapped into specific Aerospace Engineering Capstone tasks [28]

so that they can consider thousands of possible designs along the way. Modeling & Simulation enabled trade studies will support decision making along the way so that their design isn't merely a "cartoon" and a "promise," but represents a collection of diverse yet interconnected model that substantiates a viable product. They will make informal presentations and file reports along the way that the Professor and/or Graduate Teaching Assistant grades. They will also make regular formal presentations (SRR, PDR and CDR) to an external audience made up of program alumni who work in industry. These engineers supply valuable feedback to the student teams, which must be acted upon. Professor Takahashi also promises, and delivers, that the best performing teams have the opportunity to further present their work at an international professional AIAA conference. [25][26][27]

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Co-Author Takahashi structures capstone so that all teams in a given cohort design to a similar market segment, but that each team is given one or two different "launch customers." To clarify each cohort works a different segment; for example, Takahashi had the Spring 2022 work a liquid-hydrogen powered regional jet, where a prior year cohort worked a supersonic airliner, and other cohort worked a short-haul package delivery aircraft. Within each cohort, individual "buddy teams" work with different customers – usually one domestic, the other international. For passenger aircraft, one airline provides legacy full-service while the other is a low-cost; some examples of domestic full service / international low-cost would be pairing United Airlines with RyanAir. Conversely, students might have to balance the needs of a domestic low-cost carrier paired with a legacy overseas carrier (i.e. Southwest Airlines paired with Lufthansa).

Turning next to FIGURE 10, we can see how Professor Takahashi implemented the EM@FSE Entrepreneurial Mindset goals as strategic evaluation points to score student milestone presentations (example a Systems Requirements Review). The rubric is made public to the students and distributed to the outside evaluators who evaluate the presentations based on these guidelines.

AEE 468 – Systems Requirement Review – Team Presentation Score – Prof. Takahashi – SPRING 2022

Team #: ____________________

SCORE : ____________________

Exit Criteria: Is their talk well prepared and organized? i.e. Intro, Team, Team Name
EM@FSE: Can the team Articulate their design idea to diverse audiences? **EXEC / GOOD / FAIR / POOR**

Exit Criteria: Is the schedule realistic? (did you show a schedule?) **YES / NO**
Exit Criteria: Did they discuss risk? **YES / NO**

EM@FSE – Can the team Identify and work with individuals with complementary skill sets & expertise?
I.e. Do they show a plausible org chart? (Team Lead, Code, CAD, etc.)? **EXEC / GOOD / FAIR / POOR**

EM@FSE – Does the team understand how elements of an eco-system are connected? i.e. Do they have a functional decomposition figured out? i.e. Explain how the tools from the 12 mini-projects actually support deciding on wing / fuselage / engine / tail specifications? **EXEC / GOOD / FAIR / POOR**

Exit Criteria: Do you know what you are doing? (Modeling & Sim → requirements including CFR) **Y/N**
Exit Criteria: Is your process low-risk? (Modeling & Sim → requirements including CFR) **Y/N**

Exit Criteria: Have they shown requirements?
EM@FSE – Can the team defines market opportunities? - # pax, conops **EXEC / GOOD / FAIR / POOR**
EM@FSE – Can the team collect data from many customers and customer segments?
i.e. Evidence of market research for more than 1 airline **EXEC / GOOD / FAIR / POOR**
EM@FSE – Can the team critically observe surroundings to recognize opportunity?
i.e. Evidence of 14 CFR 25, 91 & 191 operations req. **EXEC / GOOD / FAIR / POOR**
i.e. Evidence of 14 CFR 25 structural design req. **EXEC / GOOD / FAIR / POOR**
i.e. Evidence of 14 CFR 25 – Interior req. **EXEC / GOOD / FAIR / POOR**

EM @ FSE – Can the team observe trends about the changing world with a future-focused orientation/ perspective?
i.e. Can they Benchmark existing and emerging competition? QFD helpful **EXEC / GOOD / FAIR / POOR**

Exit Criteria: Functional Decomposition
EM @ FSE – Can the team demonstrate an understanding of the value proposition of a discovery
i.e. can they Identify MOE (the "key" goodness criterion – fuel eff) **EXEC / GOOD / FAIR / POOR**
EM@FSE – Does the team engage in actions with the understanding that they have the potential to lead to both gains and losses? i.e. can they identify MOP (the "key" constraints for a viable design) **EXEC / GOOD / FAIR / POOR**
EM @ FSE – Does the team suspend judgment on new ideas?
i.e. do show only a broad sketch of the solution, rather than excessive detail design? **Y/N**
EM @ FSE – Is the team prepared to explore multiple solution paths, to gather data to support or refute ideas?
i.e. is there a trade study plan **Y/N**
i.e. do they have more than one idea for the Interior (basic ideas)? **Y/N**

Exit Criteria: Technical Progress Needed to Move to PDR
EM @ FSE - Applies technical skills/ knowledge to the development of a technology /product?
i.e. Showcase design tools needed to execute trade studies – completeness **EXEC / GOOD / FAIR / POOR**

FIGURE 10 - Example Milestone Review Scoring Rubric

One positive attribute of the EM@FSE goals is that they are sufficiently broad to cover a wide variety of engineering disciplines, yet focused enough to be specific for a disciplinary capstone class. Take, for example, the strategic goal of having teams "team demonstrate an understanding of the value proposition of a discovery." In the context of model-based systems engineering, the value proposition has to be codified in terms of a quantifiable metric, the Measure of Effectiveness (MOE), which serves as the "key" goodness criterion that drives the design. Similarly, the EM@FSE competency to ensure that teams "observe trends about the changing world with a future-focused orientation/ perspective" traces to a need for teams to explicitly benchmark existing and emerging competition during their initial design review.

Taken together, the Capstone curriculum embeds Entrepreneurial Mindset goals written "in plain English" that provides student teams strategic guidance to have a rich technical design experience. The fact that the market study is an essential part of the Systems Requirements Review (SRR) places the task to derive customer requirements on an equal pedestal with the need to document relevant regulatory compliance metrics and the need to showcase facility with Modeling & Simulation tools. Students are prepared to create "personal, economic, and societal value through a lifetime of meaningful work" only when these three elements are in harmony.

V. Examples of Implementation Success

In this section we will showcase three different examples of student discovery made possible through an Entrepreneurial Mindset.

For Spring 2019, the market segment was a supersonic airliner designed to fly the North Atlantic. The best technical team, which published their work at the 2021 AIAA Aviation conference, worked markets defined by SkyTeam airlines (Delta Airlines and AirFrance/KLM).[25] This team realized that a modest supersonic cruise, at Mach 1.3, was sufficient to permit comfortable daylight flights with well-timed departures and arrivals on both eastbound and

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westbound routes. Since this was not a low-boom aircraft, students could no longer assume a great-circle route; thus as shown in FIGURE 11, students worked ground track routings for their airliner designed to maximize opportunities to fly at supersonic speeds over water, even at some expense to ground-track distance; this is a brilliant example of EM@FSE(l) in action – where a conscious design decision was made to improve the overall market driven system performance by "worsening" a major design driver.

To establish Equivalent Still Air Distances, students worked up expected headwinds and tailwinds over their proposed course routings and altitudes using global winds aloft data found at the University of Wyoming atmospheric website. [29] This is an excellent demonstration of EM@FSE(q) in action where students integrated different kinds of knowledge to support and/or refute an idea. It also reflected positively on EM@FSE(o) as they understood how elements of an ecosystem (seasonal winds – far off the standard North Atlantic air-traffic pattern) are connected.

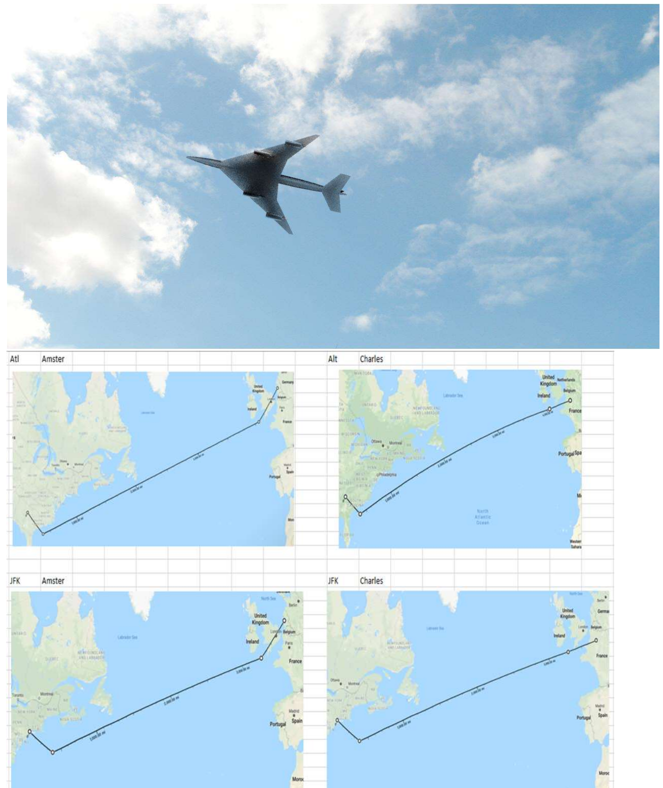

FIGURE 11 - Example Market Study from a Student Capstone Report [25]

This level of technical insight regarding fundamental requirements, and the resulting aircraft design, is unusual in a traditional aircraft sizing project (where payload/range/speed is "spoon-fed") and was only made possible because of Entrepreneurial Mindset curriculum reforms.

In the Spring of 2020, while COVID-19 travel restrictions played havoc with passenger transit, the student cohort worked a newly designed light-package, next-day parcel delivery aircraft for a variety of potential customers. The best technical team, which published its work at the 2022 AIAA SciTech conference, worked markets defined by FedEx Express.[26] FIGURE 12 documents the extensive statistical analysis the team did to identify the runway length available for both takeoff and landing, as well as airport elevations at communities currently served by FedEx Express using their Cessna Caravan fleet. This is an excellent demonstration of EM@FSE(a) in action where "students critically observe surroundings to recognize an opportunity."

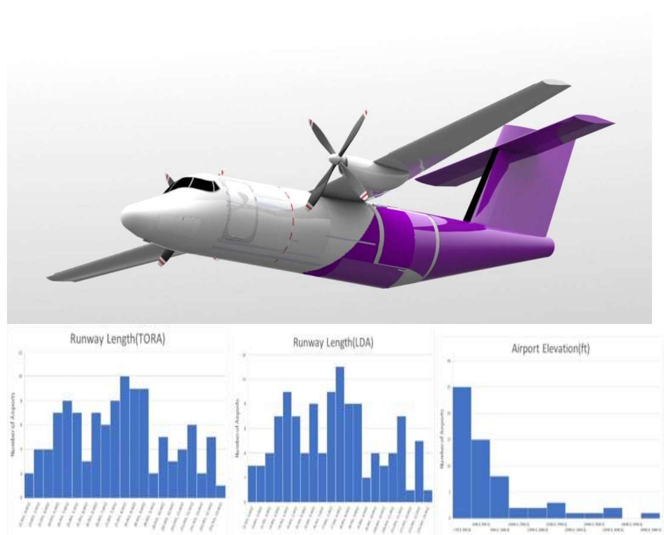

FIGURE 12 - Example Market Study from a Student Capstone Report [26]

Indeed their observations, following EM@FSE(k) "define a market and market opportunities" proved spot on. The student design turned out to be remarkably close in both technical specification and advertised performance to the

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newly revealed Cessna SkyCourier. In aviation, where "form follows function," team members were very impressed that they were able to independently infer the market drivers that Cessna clearly designed their new aircraft to match.

The Spring 2022 cohort designed zero-carbon-dioxide tail-pipe emissions regional aircraft powered by liquid hydrogen (LH2) Brayton Cycle engines. The superior team, whose paper will publish at the 2023 AIAA SciTech conference, realized that their aircraft would have most unusual mass properties due to a need to maintain aircraft balance spreading the heavy, cryogenic fuel tanks forwards and aft of the rotor-burst zone. [27] As a consequence, this aircraft had extremely "body-heavy" mass properties making it more akin from a weight perspective to an F-104 fighter plane (the proverbial "missile with a man in it") than its stubby transport aircraft wing/body/tail configuration would belie. This led to a need for extensive trade studies regarding tail and control-surface sizing; to maintain customary flying qualities, the "body-heavy" mass properties dictate disproportionately large tail surfaces. FIGURE 13 shows the sorts of complex trade studies the students had to find an appropriate tail size balancing crosswind landing capabilities with minimum control airspeed with engines inoperative. Once again, this is exactly the outcomes expected for a team satisfying EM@FSE(l) where design choices had the "potential to lead to both gains or losses."

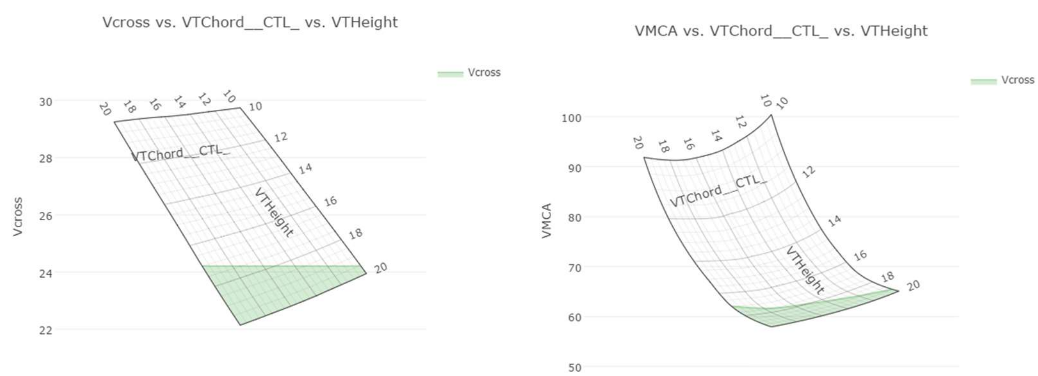

FIGURE 13 - Example Evidence of a Complex DOE Trade Study from a recent Student Capstone Project [27]

VI.Summary & Conclusions

In this paper, we highlight the positive contributions that the Kern Family KEEN grant made to aerospace engineering capstone projects at Arizona State University. The Kern Family believes, as do we, that ability to design with an entrepreneurial mindset is a defining skill of the well-rounded engineer. We have shown here that a more mature ability to design comes from students who actively participate in the requirements development process. These students have demonstrated in their capstone projects--all now published as peer-reviewed, Google Scholar indexed conference papers--that it is entirely reasonable for undergraduates to think broadly about the world around them in order to design products to fit customer desires [25][26][27] The showcased projects show how an Entrepreneurial Mindset can lead to technically "interesting" proposed engineering solutions based upon with studies showing genuine market interest.

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