

An Institution-Wide Student Outcome for Engineering: Development, Implementation and Assessment

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Abstract

The United States Air Force Academy in Colorado is an undergraduate institution whose mission is to “*educate, train, and inspire men and women to become leaders of character, motivated to lead the United States Air Force in service to our nation.*” The employer of the institution’s graduates desires well-rounded graduates with a more-homogeneous education than would be expected at an otherwise similar university. As such, the institution prescribes a large general education (or “core”) curriculum, of 29 academic courses and 93 semester hours, compared to a typical general education load of 15 - 30 semester hours. This core includes a cross section of courses in the humanities, social sciences, basic sciences and engineering. The requirement that all students complete a broad and lengthy core sequence in engineering is especially unique. Recently, nine revised Institutional Outcomes were developed to define the desired characteristics of graduates, help drive curriculum design and facilitate assessment and accreditation. This paper is focused on the “Application of Engineering Methods” (AEM) outcome, which specifies that ALL graduates be expected to:

“...Recognize the engineering and technical challenges of the Air Force mission and the physical capabilities and limits within their assigned career fields and systems. They need to not only be “users,” but to become problem solvers that use engineering principles to devise enhanced capabilities essential to achieving and maintaining dominance in critical domains. Proficiencies are organized into two broad categories:

- *Fundamental Domain Knowledge (i.e., knowledge of basic engineering principles across a variety of physical domains.)*
- *Problem-Solving Process (i.e., using a top-down, systematic problem-solving method...to address ill-defined problems.)”*

To ensure effective implementation of these new outcomes, the Academy established Outcome Teams, composed of faculty across the institution and appointed by the Superintendent (University President) and the USAFA Board. The authors of this work recently served as Outcome Team Lead and team members during the development of the AEM Outcome. This work documents this implementation process and first assessment cycle with lessons learned, benefits and future initiatives. The definition of the outcome enabled the team to re-align core engineering courses across eight engineering programs--computer science, aeronautical, astronautical, civil, computer, electrical, mechanical, and systems engineering) to create a more-cohesive curriculum that follows a development arc of increasing proficiency and challenge. In addition, the new outcome’s equal emphasis on Fundamental Domain Knowledge and the Problem-Solving Process spurred an attempt to re-balance certain engineering core courses toward engineering design and innovation.

Introduction

The United States Air Force Academy (USAFA) is an undergraduate institution located in Colorado Springs, Colorado whose mission is “to educate, train, and inspire men and women to become leaders of character, motivated to lead the United States Air Force in service to our nation”. The Academy is an accredited institution of higher learning producing graduates who obtain a Bachelor of Science, regardless of academic major and are commissioned as second lieutenants in the United States Air Force (USAF). Because the institution’s constituency desires well-rounded graduates, each student completes a 93-credit hour general education curriculum. At the Academy, this course of study is called the “core curriculum” and includes classes in engineering, basic sciences, humanities, social sciences, and military strategic studies [1, Chap7].

One of the foundational principles of the institution’s core curriculum is that it should provide “a broad liberal education that imbues in students the knowledge, skills, and habits of mind necessary for service as exemplary officers and citizens.” To do this, the 29 courses selected as part of the core curriculum must support and build proficiency in each of the nine institutional outcomes [1, Chap7].

The paper outlines the development of the current nine institutional outcomes for the USAFA. Next, it continues with a concentration on the implementation of an institution-wide student outcome for engineering titled: Application of Engineering Methods (AEM). A discussion on the first-year assessment of the AEM outcome follows. It concludes with lessons learned, benefits, and future initiatives towards improving the AEM Outcome.

Development of Current Institutional Outcomes

USAFA was uniquely accredited prior to its first graduating class in 1959 by the North Central Association of Colleges and Schools, which was the predecessor to the Higher Learning Commission—the current institutional accreditor. The institution has always used internal, external, and outcome-aligned assessment as a key part of having an evidence-based accreditation.

Accreditation for specific disciplines and reliance on adherence to an outcome-based assessment cycle was also present at the institution. This is demonstrated through the ABET accreditation of its engineering programs—the first of which occurred in 1962 for the Engineering Sciences major. This major was accredited by the predecessor to modern day ABET, the Engineering Council for Professional Development. In 1967, the following majors were also then accredited – aerospace, civil, and electrical engineering, and engineering mechanics. Astronautical engineering was accredited when added in 1973. A general engineering major was accredited in 1979, comp science in 1985, mechanical engineering in 1991, environmental engineering in 1997, computer engineering in 2003, systems engineering in 2008, and cyber science in 2016 [2].

The 1993/94 academic year saw the creation of seven outcomes specific to the academic mission of USAFA and an initial plan for assessment of these outcomes. Over the next several years as the institution wrestled with the proper assessment of these seven outcomes two concerns arose. First, the academic arm of the institution did not create, or maintain an integrated assessment

plan with centralized control and avenues for full-circle feedback. Second, no position at the institution was wholly responsible for creation and coordination of assessment efforts.

The assessment issues identified above led to the creation of a Director of Academic Assessment position in the summer 2000 and eventually to the development of a 10-year plan titled “Plan to Assess the Academic Program”. The ten-year plan included well-known commercial exams, and assessment tools developed in-house while it began on a cycle to align with accreditation visits from the Higher Learning Commission. Again, while this assessment plan represented progress it also left room for improvement where assessment measures could be better linked to educational outcomes, more direct evidence of cadet achievement could be measured (i.e. in-class tests, homework, etc.), and metrics could be taken from required course assignments rather than additional “work”.

The desire to drive towards an outcome-focused assessment approach led to the broadening of the seven academic outcomes into twenty-one institutional outcomes encompassing the academic, military, and athletic missions of the USAFA in 2006. Development of the institutional outcomes came from the overarching characteristics the institution expects a graduate to embody: responsibilities, skills, and knowledge. The institution expended much effort to further refine the outcomes with specific objectives and components to these objectives that could be aligned to courses in the core (general education) curriculum. Not surprisingly, inspectors from the Higher Learning Commission visit in 2009 were impressed with the effort, but suggested the amount of discipline it would take to sustain the assessment would be unsustainable.

Over the next few years the institution undertook parallel efforts to revise the outcomes, and redesign the core curriculum to meet foundational principles and design factors with proper accountability mechanisms in place for assessment. These efforts resulted in a reduction from twenty-one to nine institutional outcomes in 2016 identified below, and from thirty-two to twenty-nine courses in the core curriculum for the Class of 2021 entering the institution in 2017.

CURRENT INSTITUTIONAL OUTCOMES

1. Critical Thinking
2. Application of Engineering Methods
3. Scientific Reasoning and Principles of Science
4. The Human Condition, Cultures, and Society
5. Leadership, Teamwork, and Organizational Management
6. Clear Communication
7. Ethics and Respect for Human Dignity
8. National Security of the American Republic
9. Warrior Ethos as Airmen and Citizens

To ensure a complete, sustainable, and accountable assessment process, the twenty-nine (29) core courses were mapped to the nine (9) institutional outcomes and outcome teams were created. In deciding on the alignment of a core course to an institutional outcome the ability of the course to contribute to the development and assessment of the outcome were considered. The course alignment to the AEM outcome is shown in Figure 1. The outcome teams are a cross-disciplinary collection of faculty and staff who oversee the development, assessment, and

revision of the outcome. The following section discusses the details of the implementation of the AEM outcome.

Implementation of the Application of Engineering Methods Outcome

The team responsible for the development, assessment, and revision of the AEM Outcome consists of faculty and staff from across the Engineering College and those supporting the Operations Research degree. The initial task given to the team was to define the goal of the outcome, and establish the methods to assess success. A description was developed and further decomposed into specific proficiencies. These eight (8) proficiencies are organized under two (2) broad categories: fundamental domain knowledge, and the problem-solving process.

Ensuring appropriate assessment of the eight (8) proficiencies required answering the following questions:

1. What are the correct artifacts to assess each proficiency? At what resolution should the proficiency be assessed to ensure it is not too broad? (i.e. using the entire course to assess)
2. What is the correct timing for the assessments? Should they occur directly after instruction, or should students have an opportunity to develop the proficiency?
3. What are the correct performance targets? Should they be benchmarked?

Appendix A contains the details of the outcome decomposition outlined in a white paper.

Unlike previous evolutions of the assessment process, development of the proficiencies occurred first and then course mappings. In a broad sense, the categories of fundamental domain knowledge, and the problem-solving process distinguish the proficiencies that can be assessed by a stand-alone course versus those that require a development arc, notably those in the problem-solving process category. Table 1 shows the mapping between the eight (8) courses and the eight proficiencies of the AEM outcome.

Proficiencies	Foundational Courses		Intermediate Courses			Advanced Courses		
	CS 110	EM 220	AE 315	AS 310	ECE 315	CE 356	CS 210	OR 310
1: Domain-centric Systems	X	X	X	X				
2: Tech Infrastructure					X	X		
3: Problem Definition					X			X
4: Design		X	X	X				
5: Decision Making		X	X		X	X		X
6: Prototype, Test, Iterate	X		X	X			X	
7: Results, Conclusions		X					X	X
8: Reflection	X				X			

Table 1: Application of Engineering Methods Outcome Curriculum Map

Existing core courses were not required to map to a minimum number of proficiencies, or allocate a certain percentage of earned points to assessment of this outcome. Instead, the goal was to allow the goal of meeting the proficiencies drive what courses were required in the core curriculum. Ultimately, eight courses aligned to the AEM outcome. Departments specified the assignments and experiences in the course that most closely aligned to meeting the objective of the proficiency. Details of these mappings are in Appendix B. During the mapping process, the AEM outcome team also recognized that nearly all of the proficiencies are present in most of the core engineering courses. An explicit mapping with an “X” indicates key assessment points are expected and the data is provided to the AEM team for compilation and consideration. A deliberate effort was made to protect against assessment fatigue by not expecting proficiency assessment data for all development activities in the curriculum.

In addition, to ensure cadets retained skills developed to meet the Problem-Solving Process proficiencies a twenty-five (25) question comprehensive exam was created. The intention of this exam was to evaluate cadets on conceptual aspects of the proficiencies and covers topics in computer and cyber sciences, astronautics, engineering mechanics, systems, aeronautical, and electrical engineering. Administration of the exam occurs during the first course in the developmental arc taken by freshman students, CS110 - Introduction to Computing. Administration of the assessment occurs again during the final course of the developmental arc taken by senior students, AS 310 - Introduction to Astronautics. Two example questions from the exam are below:

1. What is the minimum number of bits required to represent decimal values from 0 – 40 in binary?
 - a. 2 bits
 - b. 4 bits
 - c. 6 bits
 - d. 8 bits

2. When loading a C-17 airlifter, the loadmaster places all of the cargo forward of the original center of gravity. How will this change the longitudinal (pitch) static stability?
 - a. No change
 - b. Less stable
 - c. More stable
 - d. Insufficient information

Assessment of the Application of Engineering Methods Outcome

Quantitative Assessment:

Following the end of the first semester of the AEM Outcome implementation, in Fall 2017, each of the eight (8) core courses mapped to the outcome produced an assessment report. Overall, this first data collection showed success in meeting the targets for all courses except in the operations research core course, OR310 – Systems Analysis. The assessment of Proficiency 7 (Evaluate test results and determine if a solution meets given requirements and draw conclusions) in this course resulted in an overall average of 67% below the benchmark set at 70%. Pursuit of an

explanation for the student performance revealed the final exam questions used to assess the proficiency were short answer. The AEM Outcome team members responsible for administering this course suggested the change from multiple choice to short answer format for the final exam used to assess was the cause. Currently, students complete multiple-choice quizzes during the semester and were likely unprepared for the changed format.

Additionally, the AEM Outcome assessment exam was administered to the freshman class students enrolled in Introduction to Computing and the senior class students enrolled in Introduction to Astronautics. . Figure 2 shows the results of the assessment taken by the freshmen and seniors.

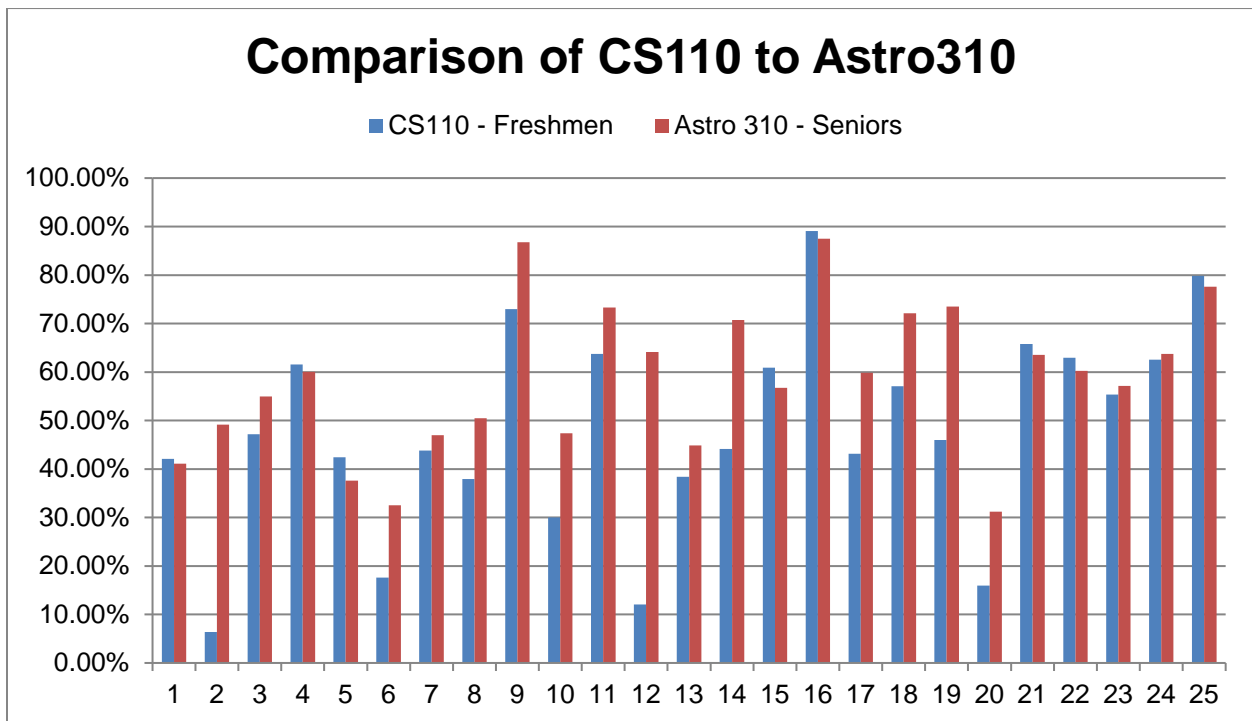


Figure 2: AEM Outcome Comprehensive Assessment Results for Fall 2017

Ultimately, the senior students scored better on seventeen (17) out of the twenty-five (25) assessment questions leading the outcome team to question why, after 3-years of engineering core curriculum, the students would score worse on eight (8) out of twenty-five (25) questions. Discussion on causes led to three main possible conclusions for the disparity. First, the scores reflect different sample populations. The Introduction to Computing students are from the Class of 2021 and the Introduction to Astronautics students are from the Class of 2018. This disparity will be addressed through further testing so that Class of 2021 scores as seniors can be judged against original freshman scores. Second, the questions developed assess the content to be presented in the developmental arc of the new core curriculum, which the Class of 2018 did not complete. Finally, the questions on the assessment may be too detailed when they should be more conceptual. The desire is for students to retain general engineering concepts and the test is “closed book”; therefore, some questions may unreasonably expect cadets to be able to perform calculations with no resources, or recent practice.

Qualitative Assessment:

Because this was the first round of data collected to assess the outcome proficiencies, the quantitative results were used to feed a discussion on the subjective assessment of courses, assignments, and benchmarks chosen as assessment mechanisms. The outcome team set out to answer the following questions:

1. Course and curriculum content mapping:
 - a. Were the courses and/or specific assignments selected appropriate for assessment of the specified proficiencies?
 - b. Were there a sufficient number of courses and/or assignments mapped to ensure assessment coverage?
 - c. Do the assignments mapped to a proficiency need to be more tightly coupled across the developmental arc of core courses to provide multiple practice and feedback opportunities?
2. Comprehensive exam:
 - a. Did the questions created to assess foundational domain-specific knowledge on the exam meet the learning objective?
 - b. Is a certain level of domain-specific knowledge required to meet the intent of the AEM outcome, or are overarching engineering concepts more important?

A significant windfall from implementing this revised AEM outcome was an emergent dialogue about the desire for a cohesive development arc across the engineering core courses. Prior to this process, the courses tended to exist in isolation, with less consideration to what proceeds and follows them. The hands-on process of mapping the courses to proficiencies, performed by disciplinary subject matter experts (curriculum directors and course directors from all of the member departments and core courses) led to numerous discussions about the current development arc, and how it might be improved; discussions which are ongoing.

For example, it was apparent that the engineering Problem Solving Process and its associated proficiencies could have different definitions, classroom activities and assessment artifacts across the various engineering disciplines, and at the various levels of student experience. This led to efforts to coordinate the introduction of design process tools within specific courses to ensure appropriate timing and consistent terminology and messaging. Such coordination should increase opportunities for courses and individual instructors to leverage the students' prior and future learning experiences in their lessons.

In addition, the mapping process also highlighted that at the Air Force Academy there is a significant disconnect between the expressed importance of design in engineering and how it is treated in the curriculum. In other words, it was clear that design topics are highly valued as an outcome of the institution, yet these topics were not being emphasized in the curriculum. This conclusion has spurred efforts to increase course emphasis in engineering design. For example, a revised version of the Engineering Mechanics core course that emphasizes design innovation is currently being tested. It attempts to weave novel engineering design methods into the traditional mechanics content in statics and strength of materials. One approach underway is to introduce

open-ended design problems that allow for imaginative ideation, using research-based design tools [3-8]. Later, the students' own design solutions can be analyzed with traditional mechanics techniques that are appropriate to the course.

Conclusions and Future Efforts

This paper describes the development, implementation, and initial assessment process efforts undertaken by a multi-disciplinary team responsible for the US Air Force Academy's *Applications of Engineering Methods* outcome. Ultimately, the team succeeded in developing an overarching objective and eight (8) proficiencies for an engineering outcome, aligning core courses to the proficiencies, and integrating an explicit cross-discipline problem solving process. As USAFA moves forward with its revised outcomes, the AEM team will continue to look at measures and methods to better assess the core engineering curriculum to produce more capable graduates. In particular, additional data will be collected on the AEM outcome comprehensive assessment exam through the time the original freshman class completes the 3-year engineering curriculum culminating in their final attempt on the comprehensive exam. At that time, a holistic view of the exam data can be examined, conclusions drawn, and future direction devised. This future direction may result in newly developed questions that may tease out more actionable conclusions

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Appendix A – Application of Engineering Methods Outcome White Paper

Graduating students will recognize the engineering and technical challenges of the Air Force mission and the physical capabilities and limits within their assigned career fields and weapon systems. These officers need to not only be “operators”, but to become problem solvers that use engineering principles to devise enhanced capabilities essential to achieving and maintaining Air Force dominance in air, space, and cyberspace. Proficiencies are organized into two broad categories:

- Fundamental Domain Knowledge (i.e., knowledge of basic engineering principles across a variety of physical domains relevant to Air Force missions in air, space, and cyberspace, and the infrastructure within which they operate).
- Problem-Solving Process (i.e., using a top-down, systematic problem-solving method, shown via italicized steps, to address the kind of ill-defined problems they will encounter across domains in their USAF careers).

USAFA GRADUATES WILL BE ABLE TO:

Fundamental Domain Knowledge

Proficiency 1: Describe and apply the principles governing the performance and capabilities of aerospace vehicles and cyber systems, and their possible effects.

Proficiency 2: Describe and apply principles governing the performance, capabilities, and defense of USAF’s critical communication, sensing, control, and physical infrastructure.

Problem-Solving Process

Proficiency 3: Formulate a *problem definition* from an incongruous set of requirements and constraints.

Proficiency 4: Create a viable *design* using robust and accepted engineering principles that considers the entire product life cycle including CONOPS, operations, sustainment, and disposal.

Proficiency 5: Apply *decision-making* skills in time-critical situations to help lead to problem resolution and objectively determine a design solution from a set of design solutions which best meets a given set of requirements. (Includes Air Force Commissioning Education Learning Outcome A2.7.2.1.1 listed under sub competency A2.7.2: Decision Makingⁱ)

Proficiency 6: Develop physical and/or virtual *prototypes* using engineering tools which are tested to evaluate candidate designs, then apply the results back into the design process to develop improved design solutions, inform the decision making process, and improve the final product.

Proficiency 7: *Evaluate* test results and determine if a solution meets given requirements and draw conclusions.

Proficiency 8: After solving a problem, cadets will *reflect* to comprehend systematic problem solving processes and the relationship to continuous process improvement. (Includes Air Force Commissioning Education Learning Outcome A2.7.2.1.2 listed under sub competency A2.7.2: Decision Making¹).

¹AFI 36-2014: Air Force Commissioning Education Learning Outcomes

Appendix B – Application of Engineering Methods Course Mapping Details

Computer Science 110:

1: The course emphasizes technology infrastructure through its Computer Systems Capabilities and Cyber Operations blocks, encompassing approximately 2/3 of the course material. Specific questions on the final exam will provide assessment data for this proficiency.

6: The course emphasizes implementation (prototyping), testing, and iteration throughout its Algorithmic Reasoning block, encompassing approximately 1/3 of the course material. A sub-score for program implementation on a programming project will provide assessment data for this proficiency.

8: The courses emphasizes the Understand – Design – Implement – Test systematic problem-solving strategy throughout the Algorithmic Reasoning block and afterwards in the course project. Homeworks, in-class assessments, multiple project submissions and the programming portion of the final exam provide formative feedback to refine these skills. An end-of-course reflection and self-assessment of systematic problem solving skills measure perceived improvements.

Engineering Mechanics 220 :

1: The course emphasizes engineering principles throughout the course, such as force balance, that govern the performance and operation of air and space vehicles. Specific questions on the final exam will provide assessment data for this proficiency.

4: The Design Project is based on a clean sheet mechanics analysis of a “B-52 Wing-Spar” redesign, including three-dimensional loading and material response.

5: The Design Project includes decision making involved in determining the right combination of material, shape, and dimensions to meet the requirements of the “B-52 Wing Spar” beam. The decision making incorporates lessons from the course as well as customer needs/opinions the cadets collect.

7: The design project will emphasize and evaluate the virtual prototypes of the “B-52 Wing Spar” with analytical results that they historically iterate with multiple attempts to improve the overall beam design.

Aeronautical Engineering 315:

1: All the subject matter in Aero Engr 315 is about how aircraft fly. However, the most practical section to Air Force officers is the performance section which is 12 lessons long and culminates in Graded Review which can be used for assessment. The performance section covers: lift, drag and power, takeoff and landing, cruise and turns. Cadets learn how far, how high and how fast air breathing vehicles can travel.

4: Cadets individually design a vehicle that meets the customer’s needs specified in a Request for Proposal. Since this is an individual project, grades will be available to evaluate B2 and B4 together.

5: The second part of the Aero Engr 315 design project requires cadet teams use a decision matrix to down select from all the individual designs to determine the best design to meet the customer’s needs. Grades for the down selection will be available for assessment.

6: During the design projects, cadets individually create designs and iterate on a spreadsheet to find an optimized design. This is proficiency will occur in a virtual environment.

Astronautical Engineering 310:

1: The course covers introductory engineering principles including space vehicle design, orbits, launch vehicles, re-entry, and space mission ops. Assessment on basic knowledge will be made using the average grade of the comprehensive final exam.

4: The design project requires student teams to design a mission to meet specific mission requirements. In addition to designing the space vehicle, students must consider the entire system life cycle, including CONOPS, operations, sustainment, and disposal. The average design project grades will be used to assess the proficiency.

6: The design project requires student teams to design a mission to meet specific mission requirements. Milestone III of the project requires students to design a virtual spacecraft prototype and determine the overall system performance based on subsystem design choices. Students are required to iterate on subsystem design choices until the spacecraft meets all electrical, thermal, propulsion, communications, structural, and attitude control performance requirements. The average Milestone III grade will be used to assess the proficiency.

Electrical and Computer Engineering 315

2: The course emphasizes principles related to electronic and/or cyber engineering in the operation of USAF technical infrastructure. The understanding of principles will be assessed via graded exams, labs, and projects.

3: The labs and design projects will emphasize and evaluate cadet's proficiency at Problem Definition. Lab and project reports will have separate graded sections associated with problem definition.

5: The labs and design projects will emphasize and evaluate cadet's proficiency at Decision Making. Lab and project reports will have separate graded sections associated with determining which solution best meets a set of given requirements.

8: The labs and design projects will emphasize and evaluate cadet's proficiency at reflection. Lab and project reports will have separate graded sections associated with reflecting upon the process used to solve the problem and future improvements.

Civil Engineering 356

2: This course covers sustainability and green engineering principles including infrastructure design, green buildings, life cycle analysis, sustainable retrofitting, renewable energy, and climate change. Building on prerequisite courses in engineering, the course develops cadets' ability to apply engineering fundamentals in complex environments. Students will use knowledge from ECE 315 to understand renewable energy systems, EM 220 to understand the use and properties of recycled materials in infrastructure, and CS 110 to understand industrial control systems.

5: Cadets will assimilate engineering information, make recommendations, and will apply principles in a cross-disciplinary problem-solving exercise. Other core courses, taken previously or simultaneously, complement this course with knowledge of Air Force mission areas in the information and energy domains.

7: This proficiency is initially introduced in EM220 with the design of the B-52 wing spar. The cadets in that course are expected to provide a written report of their design's ability to meet the original requirements, and iterate on their design based on their analytical results. In SE310, they will also complete a final design report from the semester-long project that includes the results of their design optimization approach. Their system design is judged on its ability to meet developed requirements and the careful evaluation of the design's performance.

Computer Science 210

6: Extends the introduction of software development provided by the core Comp Sci 110 course with the transition to a production-grade, text-based programming language with a full suite of features including parameter-passing, exception handling, data structures, algorithms, and recursion.

7: Formalizes software test design and analysis first introduced in the core Comp Sci 110 course.

Includes the demonstration and then development of test cases to verify satisfaction of stated requirements and coverage of the entire program. Analysis of test results leads into debugging skills and techniques to identify and resolve software flaws.

Operations Research 310

3: Cadets are introduced to problem definition while performing lab experiments in their basic science courses. EM 220 provides a formal process and practice for researching the problem and developing measures of merit for evaluations solutions. OR 310 challenges cadets to use similar problem definition techniques for a greater variety of problems with incongruous sets of requirements and constraints.

5: In the EM 220 Design Project, cadets are introduced to a formal decision-making process utilizing a decision matrix, which is again applied in AE 315 and ECE 315. OR 310 goes into greater detail by teaching a specific decision analysis approach which includes the decision matrix and other tools like decision trees.

7: Cadets are introduced to evaluating test results while performing labs in basic sciences. EM 220 builds on the introduction. OR 310 exposes cadets to multiple analytic tools and provides numerous examples for students to evaluate alternatives and refine conclusions through the use of sensitivity analysis.