# Using the Systems Engineering Method to Design A System Engineering Major at the United States Air Force Academy

**J. E. Bartolomei, S. L. Turner, C. A. Fisher**

**United States Air Force Academy**
**USAF Academy CO 80840**
**(719) 333-2531**

Abstract:
In response to an articulated customer need for more engineering graduates who can "think in systems engineering terms," the United States Air Force Academy recently began the process of developing a new undergraduate academic major in systems engineering.  An interdisciplinary team of engineering educators, computer science and behavioral science professors, employed a robust *systems engineering process* to design the major so that the needs of all constituencies would be met during a time of constrained resources.  In true systems engineering fashion, the team created a robust program architecture based on customer needs and requirements, a review of existing programs, and a forward-looking concept of operations.  The architecture not only included the curricular design, but also addressed other aspects of the system, to include organizational design, marketing, and research.  The systems engineering methodology allowed the team to establish the systems engineering major in an efficient, thorough, and organized manner.  In less than a year the systems engineering major was in place with over 30 students enrolled.  This paper will present the entire developmental process, describe the major in detail, and discuss how a systems engineering framework can be used to easily meet all ABET General Criteria.

Introduction:
 While various authors advocate many formal definitions of "system", a system may be defined as an integrated composite of people, products and processes that provide a capability to satisfy a stated need or objective. Using this definition as a starting point, Academy professors formed an interdisciplinary tiger team and applied the systems engineering process to determine customer requirements and constraints, evaluate curriculum alternatives, and developed a forward-looking concept of operations for a new academic major in systems engineering.  The systems engineering process and a systems life-cycle approach provided an excellent framework for developing the many facets of the major while simultaneously addressing ABET Criteria.
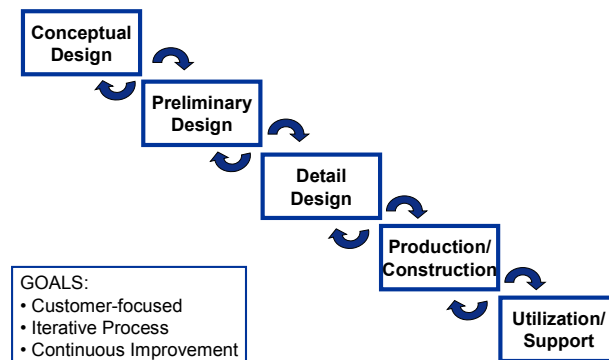
# System Engineering
## USAFA's Approach



Figure 1:  Tailored Version of Systems Engineering Life-Cycle

Conceptual Design

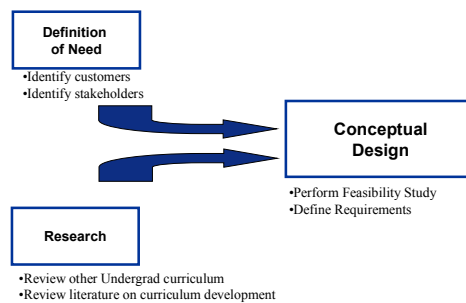## Systems Engineering Process
## Phase 1: Conceptual Design



Figure 2:  Phase 1 of the Systems Engineering Process

The first step in developing the major was the Conceptual Design phase where the team identified the customers, performed needs analysis, researched other undergraduate programs, and developed a conceptual design.

*Customer Identification:*
Our primary customer is the United States Air Force (USAF), where all of our graduates will serve for a minimum of five years.  The Air Force Academy's mission is "to inspire and develop outstanding young men and women to become Air Force officers with knowledge, character, and discipline, motivated to lead the world's greatest air and space force in service to the nation." During their four-year undergraduate program, all cadets complete a rigorous academic major in basic science, engineering, social sciences, or humanities.  Cadets interested in engineering may choose from one of the eight ABET-accredited engineering majors.  In the past, due to the highly technical nature of Air Force systems, cadets with the requisite interest and academic ability have been encouraged to choose one of the engineering majors.  Even though most of the "traditional" engineering majors, such as aeronautical or mechanical engineering, have elements

of systems engineering imbedded in their programs, the Air Force Academy did not have an engineering major *explicitly* dedicated to systems engineering.

*Definition of Need:*
*The U.S. Air Force desperately needs "airmen and a vibrant civilian workforce with science, technology, and systems- engineering skills." —Dr. James Roche, Secretary of the Air Force.*

Recent notable engineering failures and cost overruns of several major governmental acquisition projects have been traced to a lack of systems engineering principles and practices. Examples include the failure of the USAF's SBIRS satellite constellation, and a $500M cost overrun of the F-22 Advanced Tactical Fighter aircraft. As a result, our Air Force senior leadership recognized the need for engineering officers who could address cost, schedule, performance, and technical risk simultaneously within the complex acquisitions environment, to include a systems view of battlespace.

In early fall of 2002, the Air Force Chief Scientist, Dr. Alex Levis, visited the Air Force Academy engineering faculty leadership and presented an approach to systems engineering he believed would be appropriate for future Air Force officers. He explained that the senior Air Force leadership wanted a system architectures-based program emphasizing a systems-of-systems approach to systems development and operations. In this discussion, he presented a systems engineering pyramid to describe the critical elements of systems engineering, and the need for a program that would equip our future officers to influence the integration of hardware, software, and humans into large, complex systems that evolve over time; from requirements generation to lifecycle management and costs.
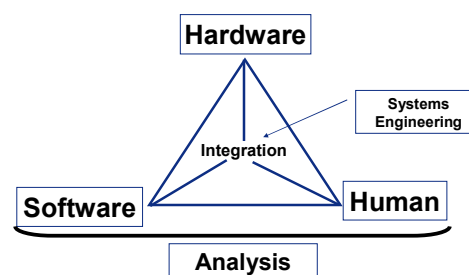
### Systems Engineering Pyramid



Figure 3. Dr. Levis' Systems Engineering Pyramid

*Research:*
With the help of Dr. Levis and other leaders of systems engineering programs, the tiger team surveyed the finest system engineering programs in the nation, including the majors currently in place at West Point and the Naval Academy, as well as base-lining the curriculums of the other major systems engineering undergraduate programs. Through this process, Air Force Academy faculty were able to better understand how the concepts of systems engineering are presented at

the undergraduate level, as well as discern the requirements for the Air Force Academy's unique systems engineering program.

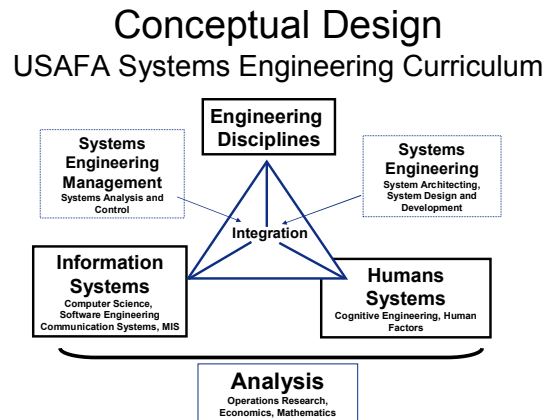*Conceptual Design of the Systems Engineering Curriculum:*



Figure 4: Conceptual Design for Baseline Curriculum

Based on identified customer needs and information of other programs, the tiger team developed a conceptual design for the baseline curriculum. The program would emphasize a system-of-systems approach, consisting of a rigorous systems engineering sequence augmented with studies in human systems, operations research, and program management. The program will also leverage the Air Force Academy's robust and broad-based 85-semester hour core program consisting of required courses in humanities, social sciences, basic sciences, and engineering. In addition, the team developed a conceptual picture of the program and translated it into a conceptual design similar to existing ABET accredited systems engineering programs. The goal of the conceptual design was to interpret the Air Force's desire for "officers with systems engineering skills" into a set of actionable requirements for the curriculum. This was accomplished through the creation of well defined Program Educational Objectives and Program Outcomes. The design of the program hinged on these well-defined requirements.

The vision for the systems engineering curriculum is to present systems engineering as a broad discipline that addresses the engineering of large, complex systems and the integration of the many subsystems that comprise the larger system. The systems engineering students will learn to consider elements of system development, verification, manufacturing, deployment, training, operations, support, and disposal. To accomplish this, they will cultivate a broad interdisciplinary knowledge across many areas of study.

The system engineering program will integrate a rigorous engineering curriculum augmented with studies in human systems, operations research analysis, program management, and the core curriculum. Cadets will learn that the systems engineering process is an interdisciplinary engineering process that evolves, verifies, and documents an integrated, life-cycle-balanced set of system solutions that satisfy customer needs. Cadets will specialize in one of nine defined option areas which include; Aeronautical Systems, Communication Systems, Computer Systems, Control Systems, Human Systems, Information Systems, Mechanical Systems, and Space Systems.

Using the <u>ABET Criterion 2.</u> Program Educational Objectives terminology, two to three years after graduation, we expect our graduates to be Air Force officers who:

1. Possess breadth of integrated, fundamental knowledge in the basic sciences, engineering, humanities, and social sciences; and depth of knowledge in the selected option sequence.
2. Can communicate effectively.
3. Can work effectively with others.
4. Are independent thinkers and learners.
5. Can apply their knowledge and skills to solve Air Force engineering problems, both well- and ill- defined.
6. Know and practice their ethical and professional responsibilities as embodied in the United States Air Force core values.

Our <u>ABET Criterion 3.</u> Program Outcomes will require each systems engineering graduate to demonstrate satisfactory:

1. Application of the fundamental concepts of systems engineering to solve engineering problems.
2. Laboratory techniques including procedures, recording, and analysis.
3. Design, fabrication, and testing techniques.
4. Use of contemporary systems engineering analysis, design, test, and management tools.
5. Written and oral communication skills.
6. Knowledge of ethical and professional responsibilities.
7. Breadth and depth of knowledge and skills in systems engineering, human systems, information systems, operations research analysis, mathematics, program management, and other disciplines necessary to effectively identify and solve the types of complex, multidisciplinary problems they will face as Air Force engineers.
8. Knowledge of the benefits and the skills needed to engage in life-long learning.
9. Ability to be effective multidisciplinary team members.
10. Skills to be an independent learner while knowing when to seek assistance.
11. Knowledge of the role of Air Force engineering officers in our global society.
12. Knowledge of contemporary social, political, military, and engineering issues.

These 12 outcomes comprehensively address the 11 specifically enumerated requirements under ABET General Criterion 3 as well as additional Air Force Academy-specific educational outcomes that overlap substantially with Criterion 3 outcomes. Other Air Force Academy-specific outcomes were considered but not included in this list since they were neither specific to engineering accreditation nor unique to the System Engineering program at Air Force Academy.

<u>Preliminary Design</u>
Once the Conceptual Design was completed, the team proceeded to the Preliminary Design Phase. During this phase, the team performed functional analysis for the entire system. A functional architecture was developed which defined the critical areas of the program. Next, the design criteria were synthesized into this architecture and the system was optimized based upon the system constraints.

# Systems Engineering Process
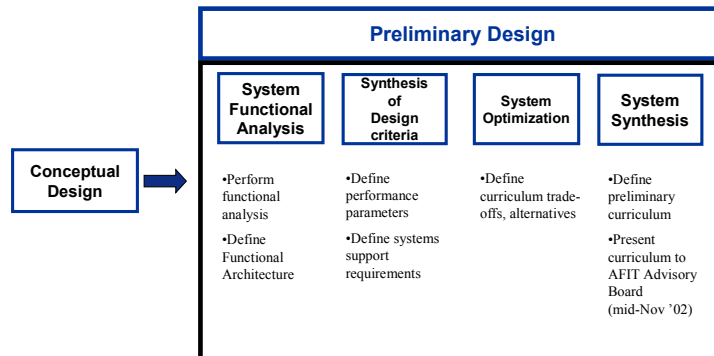## Phase 2: Preliminary Design



Figure 5.  Preliminary Design Phase

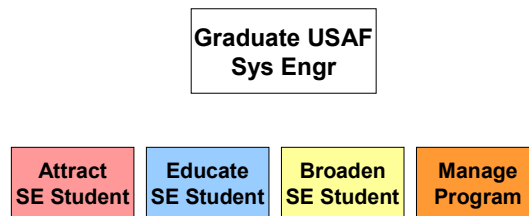*System Functional Analysis:*

## Functional Analysis



Figure 6.  Primary Functions for the Systems Engineering Program

The team functionally decomposed the system to meet the requirements of the conceptual design. The highest order function, *Graduate USAF Systems Engineer,* derived from the requirement to graduate officers who have the toolset and skills to positively influence systems engineering endeavors of the US Air Force.  Several supporting functions, *Attract SE Student*, *Educate SE Student*, *Broaden SE Student Experience*, and *Manage Program* are necessary to accomplish this objective.  Each one of these functions was functionally decomposed into smaller subfunctions.

Note:  The details associated with each function are system specific to the Air Force Academy domain.  The *Educate SE Student* functional decomposition is most germane to a wider academic audience.  Thus, it will be the focus of the remainder of the document.  The "*Educate SE Student*" function differs from the "*Broaden SE Student*" function, in that it focuses on traditional academic pursuits (i.e. classroom and laboratory settings), where the latter focuses on the breadth of experiences (i.e. research opportunities, multi-disciplinary design team participation, participation in conferences and professional meetings, visitation to Air Force and commercial engineering sites).

The next level of functions supporting *Educate SE Student* mirrors the pillars in the Air Force Academy systems engineering pyramid present earlier. In addition, an Air Force Academy unique function, *Teach Core Courses,* represents the broad-based 85-semester hour core program consisting of required courses in humanities, social sciences, basic sciences, and engineering required of all cadets.

**Educate SE Student**

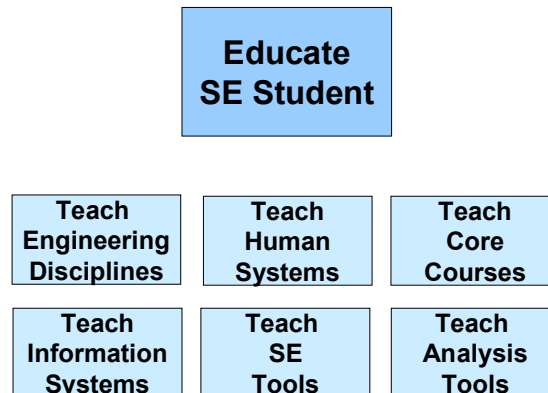| Teach Engineering Disciplines | Teach Human Systems | Teach Core Courses |
|---|---|---|
| Teach Information Systems | Teach SE Tools | Teach Analysis Tools |

Figure 7. Educate SE Student functional decomposition

For each functional area, experts on the team developed a list of the subjects and topics that would be considered for each curriculum. See figure 8 for an example.
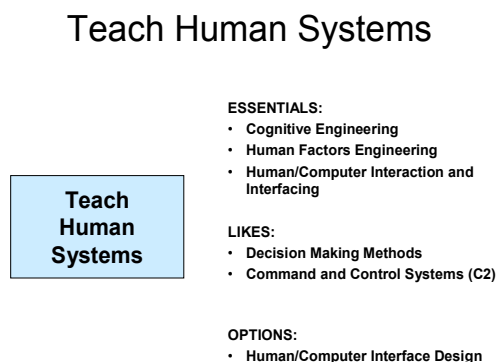
## Teach Human Systems

**Teach Human Systems**

ESSENTIALS:
- Cognitive Engineering
- Human Factors Engineering
- Human/Computer Interaction and Interfacing

LIKES:
- Decision Making Methods
- Command and Control Systems (C2)

OPTIONS:
- Human/Computer Interface Design

Figure 8. Proposed topics for Teach Human Systems

*System Synthesis:*
Based on guidance from senior leadership, as well as resource constraints, the team had to maximize the integration of the essential systems engineering topics identified with minimal new course development or modification of existing courses. To accomplish this, the team was able to develop systems engineering curricula with only two new courses and an expanded capstone design sequence. To ensure all of the essential topics for each functional area were covered, the team developed a systems engineering course sequence to capture the essential topics. Using traceability charts, topics were mapped to specific courses in the sequence, as in Figure 9. Initial

traceability charts are expanded into topic exploration matrices depicting the level of topic coverage in each course and depicting the logical sequencing, as in Figure 10.
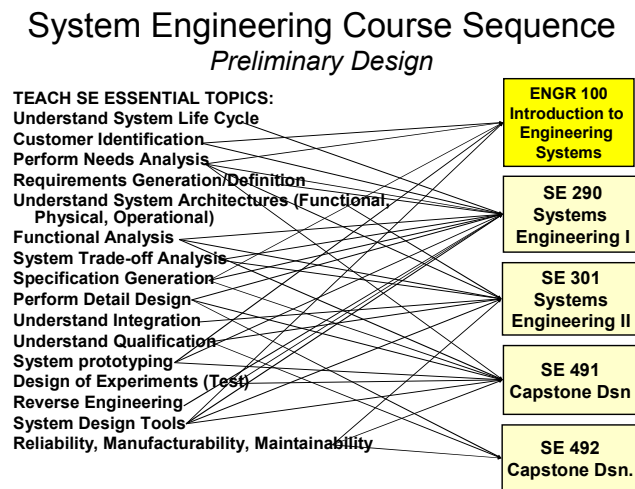
## System Engineering Course Sequence
### *Preliminary Design*

**TEACH SE ESSENTIAL TOPICS:**
Understand System Life Cycle
Customer Identification
Perform Needs Analysis
Requirements Generation/Definition
Understand System Architectures (Functional, Physical, Operational)
Functional Analysis
System Trade-off Analysis
Specification Generation
Perform Detail Design
Understand Integration
Understand Qualification
System prototyping
Design of Experiments (Test)
Reverse Engineering
System Design Tools
Reliability, Manufacturability, Maintainability

**ENGR 100** Introduction to Engineering Systems

**SE 290** Systems Engineering I

**SE 301** Systems Engineering II

**SE 491** Capstone Dsn

**SE 492** Capstone Dsn.

Figure 9.  Traceability chart for the systems engineering course sequence

| i – introduce, u – understand, d – depth, a - apply | | | | | |
|---|---|---|---|---|---|
| | Engr 100 | SE290 | SE301 | SE491 | SE492 |
| Topic | Intro to Engr Systems | Systems Engr I | Systems Engr II | Capstone Design I | Capstone Design II |
| Understand System Life Cycle | i | u | d | a | a |
| Stakeholder Identification | i | u | | a | |
| Perform Needs Analysis | i | u | d | a | |
| Requirements Generation/Def. | | i | u | a | |
| System Architectures | | u | d | a | a |
| Functional Analysis | | u | d | a | a |
| Trade-off Analysis | | i | u | a | a |
| Specifications Generation | i | u | d | a | a |
| Detail Design | | u | d | a | a |
| Integration | | i | u | | a |
| Qualification | | | u | | |
| System Prototyping | i | u | | a | |
| Design of Experiments | i | | | u | |
| Reverse Engineering | | i | | | |
| System Design Tools | i | u | d | a | a |
| Reliability, Maintainability, Manufacturability | | | u | u | a |
| Figure 10.  Topic exploration matrix for system engineering course sequence | | | | | |

Designing courses, topic coverage, and sequencing has been a distributed responsibility, with sub-teams of the interdisciplinary curriculum design team focusing on individual courses.  The entire design team reviews the overall course plans to ensure logical integration of topics and convergence among the courses in the sequence.  In addition, this integration and review function guides the development of new courses.

The first course in the system engineering course sequence is a graduation requirement for all graduates, taken during their first year, entitled—ENGR100: Introduction to Engineering Systems. Cadet teams learn systems engineering processes and tools while designing, building, and flying a boost-glide concept demonstrator system. This system combines model rocket boosters with a post-launch deployed, remote-controlled glider aircraft that must meet required performance criteria while adhering to various constraints outlined by the course instructors.

The next course in the sequence is SE290: Systems Engineering I. This course previously existed as ME290: Introduction to Engineering Design. In fall of 2003, the course integrated a systems engineering perspective whereby cadets execute the systems engineering process through the design and modification of small-scale systems in the context of a design team. Small teams employ the systems engineering process on the design of a mousetrap-powered vehicle, the performance enhancing redesign of a Nerf gun, and the development of a miniature robot for "battle" competition within a pre-defined gaming environment.

Next, is SE301: Systems Engineering II. SE301 is one of the new courses currently under development. The goal of SE301 is to examine the systems engineering process through the detailed exploration of system engineering case studies and/or DoD-relevant system integration or redesign efforts. Currently, plans call for larger cadet teams to design a modification to a military Unmanned Aerial Vehicle (UAV) weapon system. A beta-version of the course was offered in spring semester 2004.

The sequence concludes with the heart of the systems engineering program, the capstone design experience. Cadets will be given the opportunity to apply their expertise on interdisciplinary projects. Cadets majoring in systems engineering will work alongside other engineering majors to form true interdisciplinary teams. Existing engineering capstone projects include the Air Force Academy's unmanned aerial vehicle work for the Air Force, the Society of Automotive Engineers (SAE) Formula Racecar, and American Society of Mechanical Engineers (ASME) Human Powered Vehicle student competitions as well as the unique small satellite program, to name just a few.

The details of the preliminary design were presented to an Ad Hoc advisory committee for systems engineering at a preliminary design review in the spring of 2003. Based on the overwhelmingly positive feedback from the committee, the team returned to accomplish the detail design phase of the program development.

Detail Design
The team is currently involved in the Detail Design phase of the process. Course syllabi, lectures, and assignments are being developed for new courses in Systems Engineering Design and Cognitive Engineering. Multiple syllabi are under revision as existing courses integrate a stronger systems engineering orientation. By summer 2005, the curriculum should be in final form.

Systems Engineering Process
Phase 3: Detail Design and
Development

**Detail Design and Development**

**System-product
Design**

•Detail design of functional system

•Define course content

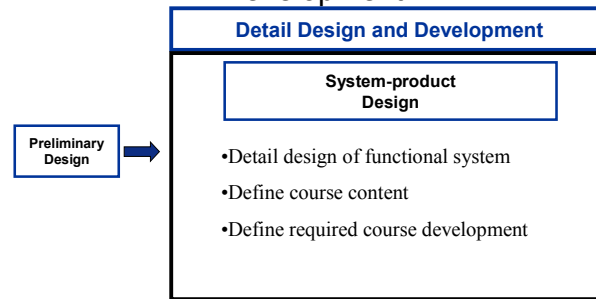•Define required course development

Preliminary
Design

Figure 11.  Phase 3:  Detail Design and Development

Conclusion:

A systems engineering approach has been very helpful in the development of a new engineering major.  Using the systems engineering process, the team was able systematically address essential activities required to ensure the creation of a robust program.  By fall 2003, the Air Force Academy advertised the systems engineering major for the class of 2006.  To date, over 30 cadets have declared Systems Engineering as their major.