AIRCRAFT AND AIR TRANSPORTATION SYSTEMS ENGINEERING CURRICULUM AT MIT

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Abstract

In the past five years, the curriculum in aircraft and air transportation systems at MIT has been expanded in response to strategic planning imperatives in Department of Aeronautics and Astronautics. In this paper, graduate programs and subjects that have been developed are presented within the context of a general framework characterizing the intellectual dimensions of these systems area. Technical, lifecycle and social aspects are addressed, and in particular the interrelationships between them. Both content and pedagogy challenges are considered. Lessons learned from offering these subjects are reported.

1 Background

Strategic planning [1] in MIT's Department of Aeronautics and Astronautics identified "aerospace systems" as a high priority area for building faculty capability, undertaking research studies, and developing educational programs. There are many gains to be made with new or improved technologies related to aerospace vehicles. However, in the course of developing the strategic plans, interviews with many aerospace leaders revealed that often the greatest challenges were at the system level and that there was a need for more academic focus on aerospace system education. This paper reports upon the Department's response to the systems challenge in the air transportation and aircraft systems curriculum.

2 Aircraft and Air Transportation Systems Framework

Aircraft and air transportation systems are large and complex, consisting of millions of parts or elements, thousands of stakeholders, and having lifetimes measured in decades. A general framework [2] that characterizes aircraft systems has emerged as faculty undertook research and curriculum development. The framework consists of three dimensions:

- A *technical* axis comprised of six levels ranging from the global environment to individual parts or lines of code.
- A *lifecycle* axis from concept definition to final disposal or retirement of the system.
- A *social* axis embodying all the stakeholders in six levels ranging from the entire society to individuals.

Interrelationships between the dimensions, and the elements within them, are an important feature of aeronautical systems, and are often associated with their complexity. The numerous interrelationships between the social and the other dimensions leads to *processes* being an important aspect of aircraft and air transportation systems. Each of these aspects of the framework are introduced in this Section before turning to the educational challenges emerging from them in Section 3 and the specific courses and programs in Sections 4 and 5.

2.1 Three Dimensions

The technical dimension comprises all the physical and information technologies that are engineered to achieve the performance objectives of aircraft and air transportation systems. It is convenient to organize the **technical dimension** into the following levels:

Level 0	Physical environment of the world
Level 1	The air transportation system (all the aircraft, airports, air traffic management system, etc.) or air defense system
Level 2	Aircraft and/or related systems (trainers, manufacturing systems, maintenance systems)
Level 3	Major aircraft subsystems or subassemblies (radar, flight control, propulsion hydraulic, power, high lift, landing gears....) comprising both hardware and software
Level 4	Components (displays, pumps, nacelles, control surfaces, line replaceable units, etc.) and major software units
Level 5	Parts (fittings, fasteners, turbine blades, etc.) and lines of code.

The levels represent some hybrid of a hierarchy such as characterized by a Work Breakdown Structure and layers such as occur in software architectures.

Many consequences of system elements with lifetimes measured in decades strongly influence the design, development and operation of these systems. Topics such as life cycle cost and the "ilities" - maintainability, supportability, reliability, flexibility, upgradability – play a central role in engineering such systems. Substructure of the **lifecycle dimension** is represented by the various phases such as:

- Concept definition
- Preliminary design
- Detailed design and testing
- Production
- Operation and maintenance
- Retirement or disposal

Many systems periodically re-enter this cycle with upgrade programs. Although these phases are more or less sequential, there is a critical need to get knowledge gained in the later phases incorporated into the early phases to develop systems that deliver best lifecycle value.

The large number of stakeholders for aircraft and air transportation systems play a critical role. Their interests vary widely and they may have different expectations for the value they will receive from the system [3]. They form a **social dimension**, organized into six levels:

Level 0	Society, nations, communities
Level 1	Extended multi-organization enterprises including partners and suppliers
Level 2	Single organizations (could be a division or business unit - may have one or more programs, projects, etc.)
Level 3	Organizational units (programs, projects, functional units)
Level 4	Working groups and teams
Level 5	Individuals

Similar to the technical dimension, these levels represent some hybrid of a hierarchy and a network in they way they interconnect.

2.2 Interrelationships or "inters"

More important than the sheer scale of these dimensions are the interrelationships, or "inters", that exist between the dimensions, or between substructure within the dimensions. An interrelationship is a "mutual or reciprocal relation or relatedness".[1] Interrelationships are many and might be characterized by increasing degrees of connectedness:

- Interconnections: "a state of being connected reciprocally" or Interface: "a surface forming a common boundary between adjacent regions, bodies, substances, or phases"
- Interactions: "mutual or reciprocal action or influence"
- Interdependencies: "mutual dependence".

It is often suggested that the "inters" are the prime source of complexity in engineering systems. It is critically important to consider

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[1] Definitions are from http://www.dictionary.com

them in the curriculum for aircraft and air transportation systems. Interrelationships between the elements of the technical dimension and within the technical-lifecycle plane are part of classical system engineering [4].

Murman and Allen [2] considered interrelationships between the social and other dimensions. Populating a matrix with the six technical and social dimension levels, they found the three major groupings:

- Human centered engineering applies to interrelationships of individuals and small groups with parts, components, and subsystems.
- Enterprise interrelationships apply between groups and organizational units with the air transportation systems, aircraft, and subassemblies or components.
- Societal interrelationships involve individuals, organizations or society interacting with the lower levels of the technical dimensions.

Considering interrelationships between the social and lifecycle dimensions, knowledge management was identified as an important "inter" for aircraft and air transportation systems. Long duration programs such as the F-16 and B-737, infrastructure such as a large airport, or systems such as air traffic control require a continual infusion of new talent that must master the historical knowledge base to effectively execute their jobs.

2.3 Processes

One consequence of the numerous social interrelationships with the technical and lifecycle dimensions is the widespread use of processes in the development, production, and fielding of aircraft and air transportation systems. Engineers tend to consider such processes as the "soft side" of engineering, and therefore not as important as the "hard technical stuff" based upon the laws of physics and mathematics. However, the scale and complexity of air transportation and aircraft systems require addressing many tasks that may not traditionally recognized as "engineering" and are largely neglected in engineering education. Examples of processes that need to be considered are:

- Systems Engineering, the basic discipline that addresses the design and development of complex systems to deliver the expected performance.
- Lean Thinking, emerging from the Japanese automotive industry that addresses elimination of waste and creation of value for the system stakeholders.
- Program Management, addressing tools and techniques to assure that complex programs are completed on schedule, within budget and with manageable risk.

With the framework as a reference, let us now turn to the challenges of developing graduate curriculum to educate students in the field of air transportation and aircraft systems engineering. Further analysis and illustration of this framework may be found in Murman and Allen [2].

3 Curriculum challenges

Traditionally, academics follow a reductionist strategy to organizing curriculum. Intellectual domains are divided into coherent sub elements within which an individual faculty member can become a subject matter expert. The curriculum at MIT and other schools is rich with excellent offerings in such sub elements in the higher Level technical (engineering) and social (management) dimensions. For undergraduates in aerospace engineering, a "capstone" course focused at Level 2 of the technical dimension and the preliminary design phase of the lifecycle dimension introduces students to the challenges of integrating their knowledge from these sub elements. Other than the capstone experience, integration of the body of knowledge represented in the Section 2 framework is largely left up to the student. It is only after several years or more of work experience that this happens, if at all. Another consequence of the reductionist strategy is that faculty members become quite specialized and often do not appreciate the important systems implications of their fields. Patterns such as these are behind the call for more systems focus emerging from the strategic plan mentioned in Section 1.

During the past five years, the authors and colleagues have focused on two graduate level programs and developed four new courses aimed at a holistic treatment of aircraft and air transportation systems. Before turning to the specifics of these in Sections 4 and 5, the framework of Section 2 serves to introduce the content and pedagogical challenges for each of these undertakings.

Content challenges that emerge from the framework include:

- Treating a wide range of technical disciplines and technologies in an integrated way
- Addressing a hierarchy of systems and their interactions
- Covering the entire lifecycle from concept definition to retirement/disposal.
- Including process related topics such as system engineering and lean practices.
- Encompassing knowledge from domains such as: economics and finance; political and regulatory factors: organizational and management principles; strategy; and market analysis.

One consequence of the scope of the content is that no single faculty member has the expertise to teach any of the subjects introduced in the following Sections. Each has a number of subject matter experts participating from industry, government and academia.

Pedagogical challenges flowing from the content challenges include:

- Addressing the synthesis and design of large-scale systems.
- Dealing with real systems rather than imperfect abstractions.
- Developing student assignments encompassing substantive learning for holistic topics.
- Limited textbooks and other codified knowledge sources for the “whole” as distinct from the “parts”.
- Addressing learning objectives for a wide range of topics in a single subject and/or as an integrated curriculum.

A final aspect of curriculum challenges specific to the structure of the Department’s master degree program relates to the number of required subjects. A total six subjects, including two math subjects, and a thesis are required for a Master of Science degree. The few number of required subjects places additional challenges on structuring the programs to encompass the breadth of topics represented by the framework of Section 2.

4 Air Transportation Systems Curriculum

MIT has a long history of research and teaching in the field of air transportation systems. In recent years, this program has been revitalized by new faculty and funding from the Sloan Foundation for the Global Airline Industry Study. With many changes in the airline industry since deregulation, the curriculum has been substantially overhauled.

The core objectives of the current air transportation systems program are to provide:

- A working knowledge of fundamental issues in air transportation systems, including:
    - Air transportation infrastructure requirements
    - Airline economics
    - Planning and operations
    - Air transport system modeling
    - System safety and security
- An understanding of the interaction between system components

Referring to Section 2, the program addresses the lower levels of the technical dimension while encompassing the entire lifecycle dimension and portions of the social dimension.

To meet the objectives, the program has developed a core course on *The Airline Industry* which serves as an entry portal to the three tracks listed below, including the recommended subjects for each track:

Air transportation infrastructure track

- Air Traffic Control
- Planning and Design of Airport Systems

Airlines operations and management track

- Airline Economics and Management
- Airline Scheduling and Planning

Air transportation systems architecting and modeling track.

- *Modeling Aerospace Transportation Systems*
- *Air Transportation Systems Architecting*

The three italicized subjects are described in the remainder of this section.

4.1 The Airline Industry

An important aspect of air transportation systems that is often underrepresented in engineering curricula are the operational considerations of those systems. The objectives of this course are for students to be able to integrate technical, operational, regulatory and business considerations at both the tactical and strategic level. The course is taught in an interdisciplinary manner with faculty from both the School of Engineering and Sloan School of Management providing expertise in their specific domains. In the Fall of 2003 ten faculty participated, including one former FAA Administrator and a guest lecture by the former CEO of American Airlines.

The pedagogical approach is to have student teams act as technical and strategic consultants to current airlines. The students analyze the actual operating performance of those airlines in the different areas covered in the course and make strategic recommendations as to how those airlines should respond to current challenges in the airline industry. The class recommendations are often forwarded to the airlines. The use of actual operational data and the real nature of the issues is a powerful motivator for the students.

The general areas covered include; Industry Overview, Regulatory Issues, Air Transportation Economics, Airline Operations and Planning, Industrial Relations and Human Resource Issues, Aviation Safety and Security, Air Transportation Infrastructure, as well as Airline marketing and Distribution. The specific lectures covered in the Fall 2003 subject are listed in the Appendix. Currently a textbook covering these general topics is being prepared by the faculty team teaching the course.

4.2 Modeling Aerospace Transportation Systems

The curriculum in air transportation systems engineering has in large part been focused on design, which is understandable given the role that our graduates have played and continue to play in the development of new and improved systems. However, successful implementation and operation of large complex systems requires engineering models that accurately reflect: the relative influence of and linkages between system components; the adaptive nature of the interaction between components; and the impact of system operation on other systems or the environment.

In the course entitled Modeling Aerospace Transportation Systems, air traffic control, airline operations, telecommunications, and other large complex systems with humans included are used as the basis for case studies that illustrate the requirements for engineering models, the tradeoff between fidelity and utility, and the role that operational procedures can play in reducing the external impact of system operation.

The pedagogical approach is to first teach the students approaches to and methodologies for modeling, simulation and optimization that are domain independent, and then through case studies involving teams of students with different backgrounds, teach them domain knowledge and how to abstract the specifics of the domain into models that capture the operational functionality

The Spring 2002 offering focused on the development of a start-up airline from the initial concept through fleet and schedule planning to the simulation of daily operation. Lectures included the following topics: Introduction to the National Airspace System; Modeling, Simulation & Optimization; Case Study 1 - Airline Operations Planning; Case Study 2 - Airspace Operations; Case Study 3 - Airport Operations. A detailed listing of lecture topics is given in the Appendix. During each of the case studies, students were required to develop models that were used in: Case Study 1 to develop the initial flight schedule, aircraft fleet and aircraft routings; Case Study 2 to determine how conditions throughout the network might impact on operations and thus how the flight schedule should be adapted; and Case Study 3 to determine how conditions at the hub airport might impact on operations and thus how the flight schedule and passenger itineraries should be adapted.

At the end of the term, the teams competed against each other in a simulated day of operations where the course faculty changed the operating conditions at will and the teams had to respond to the changes. The purpose of this exercise was two-fold. First, it illustrated to the students the limitations of the models they had developed throughout the term. Like many engineers, they began to believe that their models could capture every nuance of the real world. This belief was quickly dispelled. Second, it gave them a greater appreciation for the combinatorial complexity of operating in an environment where the performance of one component (e.g. a single airline) depends on the action of other components.

4.3 Air Transportation System Architecting

In design courses such as the senior capstone ones mentioned in Section 3, students are asked to develop a system or product design to meet a furnished set of system specifications. Since students enter the lifecycle downstream of the concept definition phase, they are not exposed to all the factors that affect the development of a viable system specification, nor the process used to reach it. To address this gap in the student's education, Air Transportation System Architecting focuses on the conceptual phase of product definition, including: technical, economic, market, environmental, regulatory, legal, manufacturing, and societal factors.

The subject is centered on a conceptual design study for a realistic system. Critical system level issues are identified and analyzed via a class team project and individual assignments. The Spring 2004 offering focused on a system concept for long haul cargo transport that would exploit the benefits of formation flying. A detail list of lectures is given in the Appendix.

The overall goal of the semester is to produce a document such as a business plan or proposal addressed to a decision maker in a position to commit resources needed to proceed with the preliminary design phase of the project. Such a document could also serve as the input for a capstone design course that could proceed with a preliminary design trade study. Three of the four offerings have led to papers submitted to professional society conferences [5-7]. A more detailed accounting of the first offering is given in Reference 8.

The subject has been offered four times over five years to a total of 61 students from aerospace and other degree programs. Aircraft Systems Engineering described in the next Section is a suggested prerequisite, but is not required. The most successful classes have had a mix of students with varied backgrounds. Those with industrial experience are better prepared for a course that covers such a wide range of topics. On the other extreme, first year graduate students may not have had exposure to dealing with ambiguous or uncertain information and to trade-offs balancing both technical and non-technical factors. All the students reported they have learned a great deal from grappling with the "fuzzy front end" of the lifecycle topics.

5 Aircraft Systems Engineering Curriculum

Systems engineering for aircraft emerged as a priority area in the 1990s in response to the strategic plan mentioned in Section 1. A small working group developed program learning objectives, curriculum structure, and a core course described in this Section. The overall objective of the program is to provide students with a foundational understanding of the systems engineering/architecture process and methodologies required to transform fundamental technical, economic and societal requirements into an integrated product solution. Collectively the student's interests encompass all three dimensions introduced in Section 2, with a centering at Level 2 of the technical dimension, the mid levels of the social dimension, and the span of the lifecycle dimension.

Each student is expected to develop their own learning objectives and course plan including recommended subjects in:

- Aircraft System Engineering (Sec 5.1)
- Air Transportation System Architecting (Sec 4.3)
- 2 elective subjects in a specialization area
- 2 math subjects, nominally one in probability and statistics, and another in optimization.

Students complete a research thesis, and are also expected to gain exposure to the practice of system engineering in a summer internship or prior industrial experience.

5.1 Aircraft Systems Engineering

Aircraft are complex products comprised of many subsystems that must meet demanding customer and operational lifecycle value requirements and operate within a global air transportation or air defense system. This core subject adopts a holistic view of the aircraft as a system, covering: basic systems engineering; basic aircraft performance; cost estimation; safety and reliability; lifecycle topics; environmental factors; aircraft subsystems; risk analysis and management; and system realization topics such as validation and verification, manufacturing, lean practices.

Borrowing on pedagogy from architecture, the course adopts retrospective analysis of production aircraft systems through detailed case studies. A large part of an architect's design education is based upon analysis of existing buildings to understand design drivers, key design decision, and the resulting success of the design in meeting the user's needs. Retrospective analysis has not been widely used in engineering, yet addresses a number of the challenges in Section 3.

The lecture topics from the Fall 2003 offering are listed in the Appendix. Each lecture is at the level of an introductory chapter to a book that would cover that subject area. There are no prerequisites for the subject and the students have varied backgrounds. Yet they are able to gain an introductory level knowledge of all these topics and at the same time see the interconnections of the full range of disciplines that pertain to an aircraft system.

The semester long case studies done by each team have several structural elements that help their execution. Just as a small team of medical students would adopt a cadaver for a semester of Anatomy, students in Aircraft Systems Engineering adopt an aircraft for the semester to explore in more detail the topics covered in lecture. The faculty arrange for a subject matter expert (SME) knowledgeable about the early phases of the program to be a resource for the students. The students are expected to find most the resource material on their own from publicly available sources. However the faculty or SME can often assist in making connections with the company to obtain non-proprietary data and reports. The case study is developed in a spiral process with four successive versions during the semester, each one adding new material while responding to faculty and or SME critiques of earlier drafts. In addition to the drafts, each team gives two oral presentations so that the other students learn something from each case study. The result is a comprehensive document about 100 pages in length covering all aspects of the origins, design, production, sales, operation, and, if appropriate, retirement of the aircraft. The resulting case studies are valuable reference documents.

The course has been offered twice to 33 students. Case studies have been completed for the B-52, B-777, F-111, F-117A, F-16, Citation X and G-IV. Students find both the lectures and the case studies to be valuable learning experiences. The biggest challenge that has arisen is to connect the two together as the sequencing of tasks in the case study does not closely follow the lecture schedule. For those interested, many of the Fall 2003 semester lectures and case studies are on MIT's Open Courseware website ocw.mit.edu under Aeronautics and Astronautics course 16.885.

6 Lessons Learned

Both the faculty and students have found these programs and course interesting and valuable learning experiences. Students have consistently responded that they find the holistic approaches of the courses highlighted in this paper to be a useful complement to the specialized subjects normally offered in a graduate program. Even though the courses have few if any prerequisites, most all of the students have been able to keep up and earn As and Bs. Guest subject matter expert lecturers from industry and government are particularly valuable and get high student rating. Indeed, it would be hard to offer these classes without active linkages with industry and government, not only for lectures but also for case studies and design challenges.

One of the interesting outcomes of these subjects is the synergy between teaching, research and practice. Although anchored as an educational undertaking, the course deliverables – both case studies and designs – are close to research deliverables. The faculty and students find that their own research are linked in with the subjects. And when industry students take the classes, the knowledge gained can be directly applied to their jobs.

Although the subjects introduced have been developed to fit the unique environment of MIT, the pedagogy used in each could be applied at other schools to fit their own needs.

7 Conclusions

New air transportation and aircraft systems engineering graduate level curriculum has been developed in MIT's Department of Aeronautics and Astronautics during the past five years. It is put in context using an overall framework characterizing the intellectual domain with three dimensions: technical, lifecycle and social. The interrelationships between these dimensions, and between the substructure within each dimension, requires a holistic approach be adopted in the new curriculum. Pedagogy and content are summarized in this paper for four new courses: The Airline Industry; Modeling of Aerospace Transportation Systems; Air Transportation System Architecting; Aircraft Systems Engineering. The courses have been well received by the students and complement the more specialized courses offered in graduate studies.

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Appendix

Specific lectures covered in the most recent offering for the courses introduced in Sections 4 and 5 are listed below

The Airline Industry

- Airline Industry Overview
- Institutional, Regulatory and Statutory Environment
- Overview of Recent Trends in the Airline Industry
- Fundamentals of Airline Markets and Competition
- Introduction to Pricing and Revenue
- Airline Operating Costs and Productivity
- Airline Pricing Strategies and Competitive Impacts
- Airline Corporate Strategy
- Airline Flight Operations
- Airline Ground Operations
- Fleet Planning and Aircraft Acquisition
- Route Planning and Network Strategies
- Schedule Planning
- Evolution of Airline Labor Relations
- Human Resource Management in Airlines
- Aviation Safety and Security
- Airport Planning and Operations
- Airport Capacity and Delay
- Overview of Air Traffic Control
- Airline Responses to Congestion Issues
- Aviation Policy and Politics
- Airline Marketing and Distribution

Modeling Aerospace Transportation Systems

Introduction
- Definition of the NAS
- History of NAS Development
- Driving Factors in NAS Operations

Modeling, Simulation & Optimization
- Requirements Definition
- Hierarchical Modeling
- Functional Modeling
- Temporal Modeling
- A/C Performance Models
- Human Performance Models
- Queuing Theory and Models
- Linear Programming

Case Study 1: Airline Operations Planning
- Demand Estimation
- Revenue Estimation
- Cost Estimation
- Schedule Generation
- Fleet Assignment
- Aircraft Routing
- Network Considerations
- Robust Scheduling
- Competitive Positioning

Case Study 2: Airspace Operations
- ATC Rules & Procedures
- Control Theory
- Traffic Flow Management
- CDM

Case Study 3: Airport Operations
- ATC Rules & Procedures
- System Study of Newark Airport
- System Dynamics
- ATC Response
- Airline Response

Air Transportation System Architecting

- Introduction of Formation Flight Project
- NASA/Boeing/UCLA Autonomous Formation Flight Program Overview and Findings
- Technical Considerations for Autonomous Formation Flying Systems

- MATECON – Method for Rapid Architecture Selection and Conceptual Design
- Systems Study of Global Range Airpower
- Economics of Commercial Cargo Operations
- Military and Commercial Cargo Mission Needs
- Market for Cargo Operations
- Architecting and Designing Air Transportation Systems
- System Level Design Issues
- Airplane Design Issues
- Human Factors for Formation Flying
- Autonomous Control
- Avionics
- Guidance, Navigation and Control
- Managing Risk
- Certification Issues
- Air Traffic Control
- System Software and Safety
- Closing the Business Case

Aircraft Systems Engineering

Part I - Systems Engineering and System Level Attributes

- Introduction to course and to the aircraft as a system
- Lean System Engineering I
- Lifecycle Considerations
- Cost and Financial Analysis
- Introduction to Aircraft Performance and Static Stability
- Transport Aircraft Performance
- Environmental Factors: Noise and Emissions
- An Airline Viewpoint: Payload, Range & Speed
- Reliability and Maintenance
- System Architecting for Safety
- The Space Shuttle: A Case Study

Part II - Subsystems: The Anatomy of an Aircraft

- Propulsion systems
- Life support, environmental, emergency subsystems
- Flight deck
- Avionics, air data, communications
- Flight Controls
- Electrical, hydraulic, pneumatic
- Structural system

Part III - System Realization

- Lean System Engineering II
- Commercial Aircraft System Verification, Validation, Certification
- Military Aircraft Systems Verification and Validation
- Risk Management
- Plant trip to Sikorsky Aircraft for Manufacturing