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AIRCRAFT SYSTEM AND PRODUCT DEVELOPMENT: TEACHING THE CONCEPTUAL PHASE

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ABSTRACT

This paper reports the first offering of a graduate level subject covering the conceptual phase of aircraft product development. The output of the conceptual phase is a system level specification that usually serves as the input for a traditional undergraduate capstone subject on aircraft design. Of critical importance in the conceptual phase is addressing the business case for the candidate product. The conceptual phase spans a much wider range of topics than the technical issues which dominate preliminary design. These include user needs, investment and business requirements, market analysis, operational issues, exogenous constraints (certification, regulation, political, etc.), as well as engineering and manufacturing requirements.

Students in the subject were required to *Prepare for the Board of Directors of a large aerospace company a compelling business case and specification for a large jet transport product*. Three student teams produced original responses to the challenge and have reported their findings in a companion AIAA paper. This paper addresses the pedagogical approaches and outcomes. These encompass the use of distance learning technology and techniques for several off-campus practicing engineering students. Overall, the outcome was very gratifying. The class will be offered in the spring of 2001, focusing on a supersonic business jet.

I. INTRODUCTION

Traditional Aerospace Engineering programs approach aircraft design as developing feasible configurations to meet a given set of mission or vehicle requirements. Undergraduate capstone design subjects and AIAA design/build/fly contests are representative examples. Within this pedagogical framework, students perform trade studies by integrating knowledge from core engineering disciplines together with manufacturing, cost, certification and other considerations to arrive at a "best" configuration. The final designs are usually based upon practical technological reasoning, leaving the student with the understanding that successful engineering is a mix of technical wisdom and experience to satisfy given requirements. One can ask if this educational experience fully prepares engineers for today's market driven economies and value conscious civilian and government customers. The challenge is to move outside the technical requirements per se and consider the other issues that determine successful products.

From a larger perspective, aircraft design is a part of *aircraft product development*, the general field of conceptualizing, designing, prototyping, and testing. It also includes the process of transition to production aircraft which are manufacturable, supportable, meet

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end user needs, satisfy exogenous constraints (certification, regulation, political, etc.) with the goal that the aircraft product provide an adequate return to investors. In considering this larger context of aircraft design, both the business strategy and the many diverse facets of how the proposed vehicle system will interact with it's operational and competitive environment must be considered.

It is well known that the most important decisions, affecting the cost of an aircraft, are made early in the program during the conceptual and preliminary design phases. Fabrycky[1] reports that about 60% of the eventual life cycle costs are locked in by the end of preliminary design. The greatest leverage to influence these costs exists in the conceptual phase of product development.

Where traditional aircraft design subjects address *how* to design an aircraft, a need exists to educate future engineers on *what* aircraft product should be designed. Both are important, but current pedagogy concentrates on only the former aspect. One measure of this is the large number of text books on preliminary design, e.g. Refs 2-6, and the lack of textbooks on aircraft product development. The most closely related text[7] covers product development from a generic framework and does not address many important aircraft specific elements.

In the spring of 2000, the authors experimented with a graduate level subject Aircraft Systems Engineering, addressing the intellectual content of the first step in aircraft product development, namely *conceptualizing a product*. The class was challenged to develop the business case and product specifications for a large jet transport. The seventeen students in the class included 12 traditional on-campus Masters and PhD students in the Aeronautics and Astronautics and the Technology and Policy Program, 4 off-campus industry students in MIT's System Design and Management master degree program, and 1 undergraduate in Aeronautics and Astronautics. The inclusion of a distance learning component added both challenges and emergent opportunities.

This paper reports the pedagogical approach, outcomes and lessons learned from this initial offering. A companion paper[8] written by students reports the resulting business case analysis. The faculty and students responded enthusiastically to the experiment and the course will be offered again in the spring of 2001, focusing on a supersonic business jet. The authors feel that similar subjects could be offered at other schools, tailored to take advantage of local interests and resources.

II. SUBJECT OVERVIEW

In designing the subject, the faculty considered the course objectives, student learning objectives, pedagogical approach, and choice of the aircraft product category. The overall emphasis was to mimic the "real world" as much as possible to enhance the student motivation and learning experience.

Course Objectives

Three objectives were established for the subject:

- Utilize a realistic aircraft system to introduce students to a total systems engineering approach for addressing complex engineering problems.
- Provide an independent assessment of a current air transportation issue.
- Develop and codify a holistic systems analysis methodology for aircraft systems.

The first objective focused on a realistic product of sufficient complexity to encompass all the relevant issues a team would face in an industrial venue. The second objective addressed the desired outcome that the class analysis would be of value beyond the classroom. The third objective recognized the need for texts or other resource material for education, training, and reference. It is hoped that through multiple offerings of this subject, such products will emerge.

Student Learning Objectives

In order to establish clear learning goals for the students and faculty, the following student learning objectives were established and communicated to the class:

- Identify and prioritize the system level issues which drive the business case and design space for the definition of a new or derivative aircraft.
- Perform an in-depth analysis of the highest priority system requirements to quantify product specifications.
- Develop a business case for a new product, including risk analysis and mitigation strategies.

The first objective was one of breadth to assure that *all* the important issues which affect a successful product were addressed, not just those which are traditionally considered within the realm of engineering. The second objective addressed the need for depth to a level sufficient to write system level specifications in areas of highest priority. The third objective addressed the critical step of having a compelling business case, including a suitable risk analysis, that could be presented to a Board of Directors for approval.

Pedagogical Approach

The pedagogical approach centered on creating a learning experience which realistically represented the challenge an industry team would encounter. In this respect, the class was given a simply stated requirement: *Prepare for the Board of Directors of a large aerospace company a compelling business case and specification for a large jet transport product.* An allowable outcome was that no such product had a compelling business case. Students were formed into project teams and the faculty adopted dual roles as 1) the Board of Directors and 2) coaches or consultants to the teams to help them achieve the project objective. The framework established for the subject is explained in the next section. Additionally, the class was expected to find relevant information or perform needed analysis, asking the faculty for any help or assistance. In a true sense, the learning experience was very open-ended with an unknown outcome. The final product requested from each team was a 20-page business plan with a one-page executive summary, an Appendix of detailed product specifications, and a set of briefing charts.

The inclusion of off-campus industry graduate students offered additional pedagogical challenges and opportunities. There were the technical constraints of low bandwidth video links, need for pre-prepared web based presentation material for off-site access, and aspects of the extended classroom such as lecturing to a camera, loss of faculty-student eye contact, and the need for electronic interruption to ask questions. Added to these were the need for non-collocated teams, competing with full time job demands of the off-campus students, and the widely varying ages and backgrounds of the students. These challenges were balanced by the broader range of experience and practical knowledge in the class, along with the connection of on-campus students to practicing engineers.

Large Jet Transport Product

The faculty selected the large jet transport product based upon the currency of the Airbus A3XX and Boeing 747X competition. It was felt that a current topic would be motivating to the students, allow them to develop their strategy in the context of the real market, and be of interest to the external community. To maintain a position of neutrality, the faculty represented the Board of Directors of a mythical world supplier of a full family of jet transport aircraft. This artifice proved ineffective as the injection of a third manufacturer did not represent the real world dynamics, and the requirement for reporting to an artificial board was relaxed.

III. SUBJECT STRUCTURE AND CONTENT

Classes

The Aircraft Systems Engineering subject was divided into two phases with oral presentations at the end of each phase. The first phase focused on identifying the key product parameters that bound the design space and business case for the large jet transport. This phase included capturing the needs and expectations of major stakeholders (end users, manufacturers, investors), market, economic, regulatory and geopolitical considerations. The second phase focused on more specific engineering and other topics necessary to develop the business case and product specification. Topics covered in lecture included: system engineering, airframe and engine engineering, air traffic management, airport and infrastructure topics, manufacturing, risk management and business plans.

Two-hour classes held twice a week consisted of a lecture followed by class discussion and analysis of the topic. This format created considerable dialog between the class members and guest speaker. The wide range of topics dictated an equally wide range of speakers, a likely feature for any subject that covers such a broad topic. The list of lectures and speakers included:

Airline Perspective
Gorden McKinzie, United Airlines
Cargo Carrier Perspective
Dale Davis, UPS Aircraft Engineering Manager
Boeing Commercial Aircraft Group Perspective
Dave Anderson, BCAG New Product Development
Airbus Industries Perspective
Rudy Canto, Airbus Flight Ops and A/C Design

Air Transportation Economics
Peter Belobaba, MIT Aero-Astro
Holistic Systems Engineering
Billy Fredriksson, SAAB Aerospace and MIT
Risk Management
Joyce Warmkessel, MIT Aero-Astro
Geopolitical Issues
Howard Aylesworth, AIA
Airport and Ground Support Issues
Tim Stull, Mrg of Systems Planning, Continental
Air Traffic Management Issues
John Hansman, MIT Aero-Astro
Environmental, Regulatory & Certification Issues
JP Clarke and John Hansman, MIT Aero-Astro
Manufacturing Considerations
Earll Murman, MIT Aero-Astro
Airframe Engineering Issues
Robert Liebeck, Boeing Co. Phantom Works
Engine Issues
George Aronstamm, Pratt & Whitney
Preparing a Business Plan
Russell Olive, MIT Sloan School

Project Teams

The class was divided into project teams, each charged to develop a response to the request for a business plan and product specification for a large jet transport. After an initial requirements evaluation phase, the students were structured into three teams of 5-6 students. One team had only on-campus students (which provided a baseline reference for evaluating distance learning effects) while the other two teams included on- and off-campus students. Guidelines for presentations and business plan content were given to the teams, but otherwise they were left to organize their activities and individual responsibilities. Teams with off-campus students used teleconferencing and electronic communication for joint work.

Assignments and Grading

Six individual homework assignments were given, each requesting a 3-5 page detailed analysis of a topic covered in lecture and needed for the project business plan and product specification. The topics included: analysis of competitors, user needs, key product attributes, functional requirements and specifications, and risk analysis. Teams were encouraged to organize their responses so that collectively they could all contribute to the team effort.

Teams were required to prepare three oral briefings of 25-35 minutes. The first covered the key product parameters, the second a review of product specifications, and the third the final Product Specification and Business Plan. Each review was followed by questions and feedback from the faculty for strong points and needed improvements. The final deliverable was the 20-page business plan with executive summary, appendices and the final briefing charts attached.

Grades were based 50% on individual contributions (30% for the 6 homework assignments and 20% for individual contributions to the final deliverable) and 50% based on team contributions represented by the two presentations and final deliverable.

IV. DISTANCE LEARNING AND INFORMATION TECHNOLOGY

Equally as challenging as the intellectual focus of the subject was the inclusion of off-campus practicing engineer students and the requirement for using distance learning technology. The design oriented nature of the subject required considerable interaction between on- and off-campus participants, including non-collocated project teams. Such needs are representative of modern industrial engineering, but are relatively new to the academic scene. However, they represent a future path for a number of educational offerings and deserve as much thought as the structure and content of the subject. Overall, the faculty found the information technology lacking in many respects for the needs. Yet, the final outcome of the subject was satisfactory.

Distance learning needs included the use of

1 Interactive electronic classroom with off-campus and on-campus students,
2 Electronic distribution and submission of class and project material,
3 Email announcements and notification
4 Teleconferencing of the project teams.

PictureTel was used for (1), MIT's COMMAND web based course management systems for (2), standard email for (3), and an analog speaker phone in a conference room for (4). Overall, the reliability of the IT systems was in reverse order of the above. Initial expectations included having remote guest lecturers, but the fragile nature of the technology led to having all lectures delivered from MIT.

Ideally, a single seamlessly integrated system is needed for all three needs, one that is available from any desktop computing system. The overhead of setting up and working with the different systems is considerable, and can significantly interfere with the learning experience. Microsoft is funding the I-Campus project at MIT which includes a component to develop such capability for subjects such as Aircraft Systems Engineering. This subject served as a learning experience for the I-Campus project, where valuable lessons were learned[9].

V. OUTCOMES

Team Projects

All three student teams produced an original response to the basic requirement to *Prepare for the Board of Directors of a large aerospace company a compelling business case and specification for a large jet transport product.* For this particular project, the business case emerged as more critical than the product specification and the emphasis of the semester gravitated in that direction. A brief summary of the key outcomes for the three teams follows.

Team North developed a Monte Carlo based probabilistic financial risk model which showed the Airbus A3XX as very risky financially. However, when considering the entire product family, the financial return on the A3XX was predicted to be a positive $3B net present value. Introducing a competing product to the 747 would force Boeing to increase margins on smaller aircraft which would lead greater profit margins for smaller Airbus aircraft. Thus the decision to proceed with the A3XX was recommended for strategic reasons.

Team East recommended forming Asiabus - a joint venture between Japanese businesses and the Antonov Design Bureau. The joint venture would take advantage of the outstanding Ukrainian airframe engineering expertise, low labor cost and abundant raw materials, along with the capital, quality manufacturing and systems capability of the Japanese. The large An-124 aircraft would form the basis for a new commercial product which provided a significant cost and time advantage. The first phase would be to incorporate western engines and avionics into a pressurized version of the An-124 for an early market penetration. A second generation product would have a new wing design for needed range and aerodynamic efficiency. The students also proposed an innovative lease-buy arrangement where customers could upgrade to the second generation product when it became available.

Team West took an Airbus perspective but recommended an aircraft smaller than the A3XX with growth potential for enlarging to the A3XX range-payload specifications. By introducing a modern aircraft to directly compete with the 747-400, a portion of the well-established existing market could be captured. As the market for a larger aircraft develops, the product would be well positioned to capture it with minimum product improvement costs. The team also recommended aggressive use of lean manufacturing and rapid product development cycle time to reduce product costs.

At the conclusion of the semester, the students initiated a request to present their findings at a professional forum. Their paper presented at this meeting[7] represents a synthesis of the three team results plus an additional analysis of the 747X product. Overall, it represents an independent analysis of this current aircraft product offering. When the class convened in February 2000, the A3XX and 747X products were frequently being covered in the news. By the end of the class in May, Airbus had announced its first order and Boeing had sent letters to its customers about the proposed 747X. And as the paper is presented, Airbus has committed to producing the A380 with the minimum 50 orders required by their Board of Directors.

Learning Experiences

Students and faculty benefited from a valuable learning experience on the conceptual design phase of an aircraft product. The open-ended nature of the early conceptual phase required many perspectives, assumptions, and considerable background information. The class repeatedly encountered the need to search the web or contact experts to find knowledge and information. Students regularly expressed interest in this holistic learning experience compared to the more traditional graduate subjects with relatively narrowly defined boundaries and assumptions. The broad range of topics addressed naturally requires multiple faculty and guest participants. It would be hard to envision having a single faculty member teaching a similar course.

The choice of the large jet transport topic was also central to the successful outcome because of its timely nature. Engaging students in a topic of current interest greatly enhances their interest and motivation. And, it also attracted the willing participation of guest lecturers. Choosing the right topic for such an offering is an important design consideration. This is also true for the traditional undergraduate capstone design subject which covers the preliminary design phase.

The inclusion of off-campus students added challenges and richness. The challenges encompassed the required use of information technology covered in Section IV as well as the formation of teams that were geographically dispersed with mixed campus and working schedules. However, the added perspective of practicing engineering enriched the learning experience of the entire class. Comments and questions from remote students added additional substance to the dialog. In a very literal way, all the participants in the course formed a learning community.

Evaluations and Assessments

Formal evaluations included end-of-semester student evaluations and more detailed student and faculty interviews as part of the MIT-Microsoft I-Campus Alliance.

Table 1 - Student Evaluations

Category	Rating*
Assignments relevant	5.2
Web materials accessible	6.7
Web materials effective	6.4
Subject graded fairly	5.6
Subject organized	5.7
Overall subject rating	6.3
Overall faculty rating	
Instructor 1	6.2
Instructor 2	6.5
Instructor 3	6.9

* Rating on a seven point scale, 1 is low and 7 is high

Results from the evaluations are given in Table 1. The subject received an overall rating of 6.3 on a 7-point scale. This is considered a positive rating at MIT. In addition, there were numerous informal comments made by students who uniformly expressed that this was "one of the best subjects" they had taken at MIT.

The detailed student and faculty interviews focused primarily on the distance learning aspects, both technological and pedagogical. A brief excerpt of key points from Ref 9 is given here.

Technological factors

There were numerous glitches as well as considerable overhead in the robust operation of the PictureTel system. Problems included occasional dropping off of remote sites, audio feedback problems, delays in switching audio and video control between sites which interfered with two-way dialog, and the lack of an easy way for faculty members to do free hand sketching or other spontaneous lecture enhancements. However, when the system was working as expected, it did provide a minimum infrastructure for a distance learning environment.

The other technological factor was the lack of a seamless integrated electronic environment. As noted in Section IV, there were four different electronic infrastructures employed. While it may be wishful thinking to hope for a fully integrated system, the lessening of any barriers only enhances the educational experience. There is still considerable room for improved IT infrastructures, which hopefully will be on the way as the Internet capability grows.

On the pedagogical side, there are numerous adjustments to make for a distant learning class. Lecture material is best done in Power Point and needs to be distributed ahead of time, as the picture quality is not good enough when using video transmission. This introduces a certain amount of rigor into preparation which has both good and bad side-effects. Although one can do a sketch using a projection camera, it is not as fluid as using a chalk or white board. Another challenge is ensuring the off-site students are engaged. The instructor has to consciously interrupt the lecture flow to poll off campus sites for questions. With only one or two students at each off campus site, they are not immersed in a classroom with other people and have a more solitary environment. On the other hand, the distant learning environment affords an extended classroom connecting students and practitioners.

Possible ways to overcome these pedagogical challenges are through a modest amount of planning and training, along with assuring a robust infrastructure is in place and supported.

VI. SUMMARY

In this paper, we report on a first experience in teaching the conceptual phase of aircraft product development to a group of MIT graduate students. Where a traditional aircraft design course has a product level specification as an input, in this course that was the output. Addressing the conceptual phase introduces students to all of the many factors which must be considered in developing a specification for a product to be a business success as well as a technical success. With a favorable outcome, the authors plan to offer the class in future years. Variants could be tailored to the resources and interests of other institutions.

An important element in the successful first venture was picking a target product which was of current interest, the large jet transport. This provided a high level of interest among students and speakers, and made the subject very current. The conceptual phase of product development requires addressing many factors, far beyond the capability of a single faculty member. The authors found that engaging guest speakers was very effective and both students and speakers responded enthusiastically.

An additional component to the subject was the inclusion of off-campus practicing engineering students via distance learning technology. This provided challenges and benefits. The distance learning technology is still very fragile and lacks integration among the various modes (video, web, e-mail, audio). This leads to additional teaching overhead as well as pedagogical adjustments. However, the extended classroom of bringing practitioners in contact with traditional students provides a richer, more relevant learning environment.

Overall, the first offering of thisch subject met both the course goals and the student learning goals. It was fun to teach and received an enthusiastic response from the students who enjoyed the holistic view of aircraft development.

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