Experience in Multidisciplinary Design Education

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Abstract

Recently multidisciplinary design optimization (MDO) has become recognized as a new and important discipline in engineering. We have been conducting research in this area for a number of years. In doing the research we have had graduate students working in MDO teams for a decade. We have also introduced MDO into the undergraduate curriculum. We started with a pilot project in MDO in 1990-91, working with one senior design team. After this experience we started using smaller, more well defined MDO problems. We formed a center in 1993: The Multidisciplinary Analysis and Design Center for Advanced Vehicles (the MAD Center). In the fall of 1994 we began offering a senior-graduate level course called Multidisciplinary Design Optimization. We have also started a formal graduate MDO certificate program This paper discusses our experiences with these efforts.

Introduction

The general state of engineering education has been criticized in the last several years by industry.[1,2] A large part of the problem was considered to be related to "design education," which is the only *engineering* component of most engineering programs. This may be particularly true in the heavily science-oriented aerospace curriculum, which was critically examined at about the same time by McMasters and Ford,[3] and Nicolai.[4] Simultaneously, many engineering educators were also expressing concern, and the ASEE devoted an entire issue of their magazine to the problem.[5] The aerospace curriculum was also examined from within, notably by Covert[6] and Roskam.[7] NASA had also recognized a problem and had instituted a program to improve design education known as the NASA University Advanced Design Program,[8] which was run by the USRA for a number of years. This is the broad context within which we are addressing one aspect of the problem. It involves producing graduates with a knowledge of emerging formalized design processes.

Several recent reports[9,10] on US competitiveness and the role of engineering education have identified the need to introduce formalized design methodology into engineering design education. One approach appropriate in aerospace engineering is multidisciplinary design optimization (MDO). Multidisciplinary design has become an important area for vehicle design. It represents a formalization of the design process and is becoming necessary for several reasons: i) new vehicles are being required to attain performance levels well beyond levels previously obtained, ii) the traditional aircraft designers that worked on many projects during World War II and the early jet era of the 1950s are essentially gone, and iii) vehicle demands (*e.g.*, the National Aerospace Plane or NASP, and the High Speed Civil Transport or HSCT) are so different that the knowledge based approach that was available to the previous generation is essentially invalid for many of today's problems. The role of the government in promoting multidisciplinary design as an identifiable research area is new. The problem of even maintaining existing design capability was identified as an issue in a recent Rand report.[11] They noted that there was no government advocacy for advanced design methodology for complete systems. This is now changing, and the government role was almost entirely due to the vision of one man, Dr. Jaroslaw (Jarek) Sobieski.[12,13]

The basic ideas of multidisciplinary design have evolved to the point that specific algorithms have been developed that can be used on actual design projects for entire vehicle systems. Consistent with the goals of the studies described in Ref. 9 and 10, one means of getting these more formal design approaches adopted in industry is to train engineering students to use the methods.

At Virginia Tech we have been working on multidisciplinary design with graduate students for many years. Most of this work has been directed toward the combination of structural and aerodynamic optimization,[14-17] although the role of control requirements has been incorporated also.[18] The cited references provide a glimpse into the results of some of our recent work. A key concept has been the use of the variable-complexity approach. Using that approach we combine both detailed, computationally expensive, methods and simple, computationally inexpensive, methods to make MDO affordable. In some cases we have also been able to develop procedures based on the simple methods alone.[19,20] Although this approach can provide rapid insight into the configuration design issues, it must be used carefully since optimizers exploit the weaknesses of the analysis methods. The simple methods are particularly vulnerable in this regard.

We have started to include multidisciplinary design and optimization methods in our classroom instruction. A first step at Virginia Tech toward the introduction of this methodology was undertaken in 1990-1991 by having one group of senior aerospace engineering students use MDO. This was a special project using one senior design team to do a design following a more formal multidisciplinary approach. The project produced an AIAA Paper.[21] It proved to be successful, although we found that the students needed more background in traditional design before the formal multidisciplinary design work could be undertaken effectively.

More recently (September 1993), we have established the Multidisciplinary Analysis and Design Center for Advanced Vehicles (the MAD Center, see our web page at http://www.aoe.vt.edu/mads.html). We have also started a graduate design program, featuring MDO, and won one of the NASA Multidisciplinary Analysis and Design Fellowship programs. In the fall of 1994 two of us (Gürdal and Haftka) gave an MDO course, which was taken by seniors and graduate students.

With all this activity, it appears useful to share our experiences in a paper. This paper contains the following:

1. Experience with the senior design project of 1990-91 with hindsight.
2. Examples of multidisciplinary aircraft design with simple examples for use in the classroom based on previous work.[22]
3. Experience from the MDO course of Fall 1994. Mathematica™ was heavily used, and the model problems using Mathematica™ will be described.
4. A brief description of the role of multidisciplinary design throughout our curriculum will be presented, including the new graduate design program.

1. Experience with the 1990-91 senior design project

Background: The Normal Senior Design Approach

The senior aircraft design program at VPI is a two semester sequence. One of us (Mason) is responsible for this course. For approximately the first half of the first semester the students work on individual assignments. Although they may work together collecting information, each student must submit entirely original work. There are four individual assignments. The last three are specific to the aircraft design problem that they will address in their teams during the rest of the year. The individual assignments include:

1. Fabrication and flight evaluation of a tissue and balsa model aircraft.
2. Evaluation of comparator aircraft that currently exist and may nearly satisfy the design mission.
3. Development of a traditional aircraft sizing program and initial estimate of TOGW.
4. Development of an aircraft concept sketch (three-view drawing) to meet the mission.

After the individual assignments, the students start working together in teams of 8-10 members. The first step is to consider each team member's design concept, and select three concepts to evaluate in more detail. A mid-term presentation is then made describing this process and the plans and metrics to be used in selecting one preferred concept for more detailed preliminary design. The second semester is purely a team effort.* The objective of the second semester is a complete preliminary design and a final formal presentation of the design. The final report is either a proposal responding to the RFP in the AIAA/Lockheed undergraduate team aircraft design competition or a report describing the work done on any other project, as appropriate.

The make-up of the design team is typically:

-Leader
-Aerodynamics
-Stability and Control
-Systems
-Configuration Designer
-Propulsion
-Structures/Materials
-Weights
-Performance/Mission Analysis

MDO Pilot Project Design Team

With support by NASA Langley for a graduate student, in the 1990-1991 school year one senior design team at VPI used the methods of multidisciplinary optimization in their design project. The project title was "Pilot Project: Multidisciplinary Design Approach to Aircraft Design Education." The students in the special MDO group did the same individual assignments that the rest of the class did. Their design was broken up by

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* At Virginia Tech we now also have selected freshmen participate in the senior course during the spring semester as part of an NSF SUCCEED Coalition Megaproject on Early Design. This program has proven to be an outstanding success.

discipline as described above. However, in addition two team members worked primarily on optimization.

Several approaches to multidisciplinary optimization (MDO) are available. As a basis for this multidisciplinary design exercise, the method by Sobieski[23] for global sensitivity evaluation was used, as outlined in his review of the subject.[12] Sensitivity analysis is the term often used for the process of calculating the derivatives of the system response or system constraints with respect to design variables. Such derivatives are required by most popular optimization algorithms. It is generally recognized that for most problems involving complex problems, sensitivity analysis is responsible for the major computational cost of system optimization. In the case of multidisciplinary optimization we often have several disciplines that are interconnected. The output of one discipline becomes the input for another. Usually each discipline has analysis codes that can furnish derivatives of their output with respect to their input parameters. These derivatives can be obtained analytically or by finite differences. However, because of the interdependence, derivatives with respect to system design variables require taking account of the interdependence. Sobieski proposed the general framework for computing system derivatives from disciplinary derivatives including the interdependence properly.

The MDO method was applied to the mission defined by Boeing for the 777. The Boeing project was formally started shortly after the students started working on the project, making the project timely and especially interesting for the students. The team used the global sensitivity analysis method to determine system sensitivities and a linear programming code employing these sensitivities to make four steps in the optimization process. Takeoff gross weight was selected to be the figure of merit in the design process, and after four steps in this process this weight appeared to be converging to a final value. The school year ended before another iteration could be made. However, after four iterations the students had become well acquainted with the process, and the primary educational objectives had been accomplished.

In the case of the MDO group, the configuration was selected at the mid-term presentation in the first semester. The initial sizing of the concept was then carried out using ACSYNT.[24-26] This was done to allow more time to concentrate on the MDO problem formulation at the end of the first semester and start the detailed process the second semester. The student responsible for each discipline obtained the local sensitivities for his discipline. These local sensitivities were then given to the team members doing the optimization.

First the global sensitivities were obtained, and then effects on the design from each discipline were examined collectively. Examination of the global sensitivities initially led to questions about the formulation of the sensitivity matrix, and resulted in the reformulation of the sensitivity matrix several times. After the global sensitivities were examined, they were used in a linear programming code (STORM), with design variables constrained to move a maximum of ten percent. The execution of STORM resulted in a new design (actually new values of the design variables), for which the local and then global sensitivities were found and the optimization step repeated. Although optimization was done, an emphasis was placed on understanding the effects of the design variables on each discipline and their resulting effects on the entire vehicle. Hopefully, all aspects of the process remained visible to the students. Thus, at the expense of computational efficiency, no automation of the overall process was employed.

Special Aspects of the Project

Seminar on MDO: To give the students a description of the MDO process, Dr. Sobieski came from NASA Langley Research Center, and gave a lecture to the entire aircraft design class in September 1990. This talk, "Everything Influences Everything Else: A Designer's Dilemma and a Math That Can Help," and the hardcopy of the viewgraphs, provided the basis for the MDO group's work.

Seminar on human factors: To balance the technical optimization aspects of the course, we invited Paul Kemmerling, a Virginia Tech faculty member with over twenty-five years of USAF experience in human factors, to describe some of the other issues that should be considered in design.

Software Base: To obtain the system sensitivities, a computational methodology is required for several disciplines. Although various computer programs were available, the MDO project demanded that the codes be organized into a uniform collection, each working in a similar fashion, and with a uniform approach to user's guides. The primary activity of the graduate student being supported under NASA funding was to collect the codes and create a directory on the VPI VAX with the programs installed. Together with the VAX directory, a set of user's manuals was collected and edited into a package available for student copying at the local copy center. (This library has since been moved to the department workstation and PC network)

Although the initial intent was to compile the manuals into a single volume, it became apparent that this manual would be too large to use easily, and too expensive. Thus the manual was divided into volumes by discipline, and students could select the volume to purchase. This set of programs continue to be used, forming the core of the VPI AeroTools library of codes. The manuals are under continual revision as students identify portions that are unclear, as well as typographical errors. The manuals are being converted to html for use in an entirely electronic environment in the future.

Results

The results of the effort were documented in the group's final design report. A three surface configuration was selected. One of the main interests in the work was to see if either the tail or canard would "disappear" (surface area going to zero) during the optimization steps. The design progressed through four design iterations, and the weight was decreasing, and appeared to be approaching a converged value. The aft tail surface area decreased during the iterations, but did not vanish. However, further iterations might have resulted in a canard configuration.

The group wrote an AIAA paper on their design project,[21] and the details of their work are contained both in the AIAA paper and the final design report. Since the students had graduated, the final design report was not revised after the instructor's comments were annotated.

Based on the experience with the design class, the graduate student that was supported to collect and help the undergraduates use codes to model the various disciplines, developed a program to carry out multidisciplinary design directly using analytic technology models as a Master's Thesis.[19,20] Although this code did not directly influence the 1990-91 MDO design group because it was not available until the end of the year, it has become a useful program. In succeeding years several design groups have used it, and it formed the basis for a model problem used in our MDO course described below.

The effort resulted in four reports and a collection of computer programs and manuals. Table 1 lists the programs that we had available at the end of the pilot project. An updated list of programs in use at Virginia Tech is available in a recent software review paper.[27]

Retrospective, Lessons and Subsequent Development

The use of MDO in a student design environment presented an interesting challenge. After experience with these students and the subsequent construction of an MDO design program using analytic technology models, we now have some insight into the use of MDO in design education. Some things have become apparent. We also learned things which are much broader, applying to many aspects of engineering education.

- The interactions between disciplines continue to appear complicated to undergraduates, even when addressing them in the global sensitivity context. In particular, the use of partial derivatives and the chain rule confused them. Figuring out what to hold constant, and what to allow to change was difficult sometimes. An example was the requirement to maintain a trimmed condition during configuration perturbations. This can interact with control surfaces and weight. The requirement we imposed of maintaining a fixed range also introduced confusion. The process requires thought. In an educational environment this is good. It appears however, that great care must be taken in setting up the contributing analysis, and understanding the true connections. This experience led us to conclude that the students needed more well defined MDO problems to use as building blocks to the application of MDO to an entire system, where they had a lot of freedom.
- The computer codes must be capable of handling the variety of configurations that the students are interested in. Although we refuse to let them use analysis difficulties as an excuse not to pursue various design concepts, we recognize the difficulty. This challenges the students to be creative in modeling their problems. Although some students are not entirely pleased with this approach, this aspect of the MDO project was probably one of the most important in trying to illustrate the typical engineering approach to problems as opposed to pure science. One specific difficulty, the need for a methodology to trim three surface configurations for the smallest trimmed drag, has subsequently been addressed by implementing a version of the trim scheme described in NASA TP 2907.[28]
- The students seemed to like working on something new. However, they expected the instructor to solve their problems for them, and were quite willing to "give up," and wait to be told what to do.[*] In general we did not allow the students to do this. They were urged to identify their problems clearly, propose a solution, and then try it out. This was usually associated with problem formulation. Primarily this involved understanding how the variables were related, and then figuring out how to compute gradients with codes not specifically setup to do this. Solutions to these problems frequently required some extra effort and imagination. During the course of the project, many of the students demonstrated obvious growth and increased maturity, especially during the second semester. The increased focus on problem solving in this pilot project was probably better for the students than the focus on final details and proposal writing required of the teams competing in the AIAA competition. The best educational program is probably a combination of the two approaches.
- After the pilot project was finished, we constructed a PC level program that used analytic models to represent the various disciplines. This allowed rapid study of the complete system. This program has been used in the general design course, as are the computer tools and manuals. We are also gradually increasing the use of explicit multidisciplinary design methods in the second semester of the design course. Here we are trying to satisfy one of the key recommendations of the national design panel (Ref. 10). By having this work in the beginning of the second semester, many students will already have taken the new MDO course.

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[*] This attitude was recently identified as a major problem in maintaining corporate competitiveness by a former chairman of IBM.

- Another development in our curriculum resulting from our experience in trying to formalize the design course to include advanced design techniques was the introduction of mini-design projects in virtually every course. One of us (Haftka) initiated this approach after interviewing a dozen or so of the design students. It was clear that they needed a bridge between the open ended engineering work in the design class and the closed ended well prescribed problems that they were being assigned in their engineering science classes. Thus mini-design projects were introduced into the junior level structures and vibration and control courses. These mini-design projects took the form of a series of homeworks that tackled the same design problem, but showed the student how he could do a better job as he learned the new tools. For example, in the first structures course a series of wing-box design problems were developed. The wing was designed against strength failure. When the students came into the course they were asked to design the box as a tube, because this was the only structure that they knew how to analyze for both torsion and bending. As the course progressed they had assignments based on an I-beam section and then a closed box, and they saw how the weight dropped with the more efficient concepts. Mathematica™ waso featured in this series of mini-projects.

2. Examples of simple multidisciplinary aircraft design class problems

After the initial experience with a senior design team working on the entire system design using MDO, we started to work with smaller, more well defined problems to illustrate the importance of considering several disciplines at the same time. Many of these problems addressed the trade between increasing wing thickness to reduce wing weight and reducing wing thickness to reduce drag. These examples used the same simple technology models[22] we had used previously in developing our model problem MDO code.[19] One example of this class of problems is discussed below in Sec. 3.

In 1994-95, one of our teams worked on the problem of injecting propane into the antarctic atmosphere to replenish the ozone hole. This problem led to the use of supersonic aircraft that had to make numerous passes over the antarctic, including a 180° turn. The issue of what *g*-level was best for the turn needed to be solved. A low *g*-level required low levels of additional thrust, but took a long time, resulting in the use of a lot of fuel. A high *g*-level turn took less time, but led to higher thrust requirements (engine weight), and also used a lot of fuel. It appeared that there was an optimum *g*-level, and the MDO problem became one of finding the best *g*-level. This is a problem that can be solved easily, but some of the seniors still struggled with the formulation.

Figure 1 shows the result of considering both the fuel and engine weight. This case corresponds to a Mach 2.4 turn. The minimum fuel use occurs at a *g*-level, n, of 1.7. The engine weight required to make the turn increases monotonically with increasing *g*'s. The minimum total weight occurs at $n = 1.25$. However, according to the student's analysis, this condition did not size the engine, and the engine had enough thrust to make a 1.6 g turn, which only used forty pounds more fuel than the minimum, while saving several thousand pounds of engine weight compared to the 1.7*g* case.

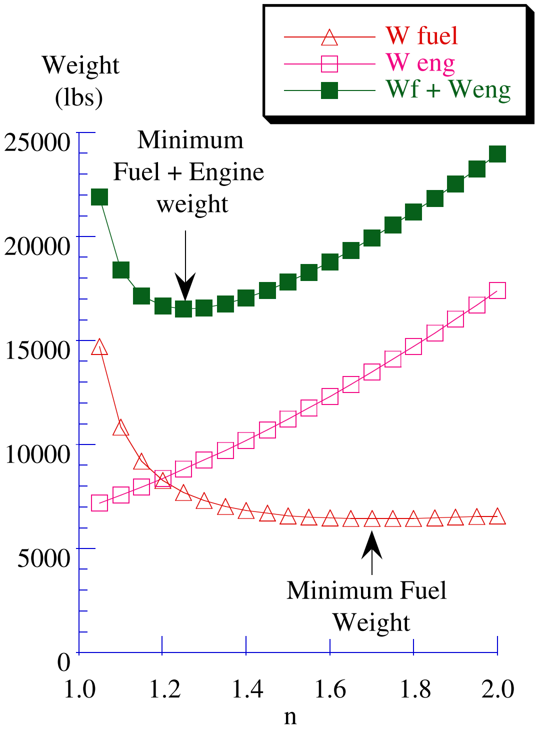

Figure 1. Simple MDO example: Fuel required and engine weight.

3. Multidisciplinary Design Optimization (MDO) Course

Partly in response to our experience with the pilot project, and as part of the MAD (Multidisciplinary Analysis and Design) Center activities, we decided to incorporate concepts, methodologies, and the applications of multidisciplinary design optimization into the curriculum. Rather than developing an entirely new course, we decided to adapt a course which was part of the current curriculum along the lines of multidisciplinary optimization. The senior level course "Engineering Design Optimization" (AOE/ESM 4084), which is a cross-listed course between the Department of Aerospace and Ocean Engineering, and the Department of Engineering Science and Mechanics at Virginia Tech was ideally suited for that purpose.

AOE/ESM 4084 was originally designed to introduce the use of the methods of mathematical programming for engineering design optimization. The methods taught in this course included linear programming, unconstrained nonlinear programming such as the steepest descent, conjugate gradient, and Newton's methods, and constrained nonlinear programming such as the penalty function approach, sequential linear programming, and sequential quadratic programming approaches. Applications of these methods to minimum weight design of structures, machine design, and appropriate design problems from other engineering disciplines were demonstrated.

Most of the material in the original course was needed for the MDO course. In addition, new material on MDO specific topics such as the introduction to MDO formulations and the Global Sensitivity Equation method, described above, was needed. Also, instead of the small, mostly textbook examples, typically used in the course, we needed to have the students solve more complex problems that had enough MDO content. The problem of squeezing more material and more complex problems into the same time period was solved by extensive use of Mathematica™. With Mathematica™ available to the students, solving complex problems became much easier, and as explained below, Mathematica™ also enabled us to present optimization algorithms better and faster to students.

The other major modification of the existing course to emphasize the multidisciplinary optimization was to incorporate examples of multidisciplinary optimization to demonstrate the basic tools. In practice, however, including design examples from different disciplines into a senior level course is difficult. Such examples require the students to have at least a rudimentary knowledge of the analysis techniques used in those disciplines. The difficulty is mostly associated with the complexity of the analyses needed in realistic multidisciplinary problems which commonly include aeromechanics, structural mechanics, and sometimes controls and materials. Additionally, the content of the existing course was already crammed with too much material. Therefore, the inclusion of the two items discussed above, the sensitivity derivatives and the multidisciplinary design problems, seemed unrealistic.

A solution to the difficulty described above was obtained based on a two-pronged approach. First, we decided to introduce the use of the PC based package Mathematica™ into the course as mentioned above. Second, rather than introducing multiple examples, we decided to include a single multidisciplinary design problem that we introduce early in the semester and then use it repetitively to teach and demonstrate the different aspects of the different optimization methods.

The use of the Mathematica™ program, which combines symbolic manipulation, programming, numerical calculations, and graphics features in a notebook environment that can be used to deliver electronic lectures, was crucial for the success of the course. A number of Mathematica™ notebooks were prepared to demonstrate the steps of various optimization algorithms. These notebooks were on linear programming, sequential linear programming, Powell's conjugate directions, steepest descent, Fletcher-Reeves conjugate gradients, Newton's, sequential simplex, penalty function approach, method of feasible directions, sequential quadratic programming, and global sensitivity derivatives. These notebooks were used to present live demonstrations during the lectures via projection panel hooked up to a laptop computer. The notebooks prepared for the lectures were also made available to the students as tutorials that could be worked out outside the classroom environment to gain practical experience on the subject by performing the derivations and solving numerical examples. The advantage of the Mathematica™ notebooks over some of the multimedia programs which allow the students to go through only a fixed number of preestablished steps is the unlimited number of variations that the students and instructors can create during the tutorials.* Another advantage of the use of Mathematica™ was that it permitted the students to tackle nontrivial design problems as homework problems and projects.

One of those nontrivial design problem was the multidisciplinary design optimization example chosen for the course. The problem is based on the method developed by the graduate student who worked on the MDO Senior Design Pilot Project described above. The paper written to illustrate the use of simple technology models investigates the use of various analytical models to provide insight into the technology integration issues in multidisciplinary aircraft design.[19,20] Simple algebraic models are used to demonstrate the key interactions between structures, propulsion, and aerodynamics. Despite their simplicity, it was not appropriate to expect the students in the class to program these into design codes as their class project during an already loaded single semester course.

Instead, we have adapted a strategy to gradually introduce the students to the problem by first asking them to write the equations provided into a Mathematica™ notebook so that they can literally play with the equations.

The first homework of the semester was, therefore, to use Mathematica™ to make plots of the total cargo weight of a transport aircraft with given nominal properties with respect to the wing aspect ratio, wing area, sweep angle, and Mach number. The problem is given here as Table 2. After that, depending on the topic under consideration during the various stages of the course, the same problem was assigned repetitively. The next problem was the graphical maximization of the cargo weight as a function of the Mach number and the wing area with a constraint on cruise lift coefficient. Later on the same problem was solved using sequential linear programming. The number of variables was increased in the following problem, which posed it as a

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* Indeed, several students taking the course used variations on the MDO class problems in their aircraft design projects in 1994-95.

sequential quadratic programming problem with Mach number, wing area, wing thickness ratio, taper ratio, aspect ratio, and sweep angle design variables. Finally, the same problem was used to solve for the derivatives of the total take-off weight and the lift coefficient with respect to the Mach number and the wing area by using the global sensitivity equations.

To get a feedback from the students on the material covered during the course and the way the material was presented to them, a survey was given at the end of the semester. Fourteen students participated in the survey. The survey questions are given in Table 3, along with the number of students (presented in square brackets) who chose the various answers. Because of the small number of students in the class, it is probably not appropriate to make sweeping conclusions about the results of the survey. However, there are some indications of the success achieved in using the approach described above during the semester.

One of the concerns we had during the semester was the varied backgrounds of the students. Less than half of the students in the class were Aerospace majors. Therefore, the majority of the students did not have any background in aircraft design.

Some of the questions in Part B) of the survey were intended to find the reaction of the students to the use of an aircraft design in the course. Despite the fact that half of the students found the problem to be a difficult one (see Question 9), most of the students found the problem to be useful and its frequent use to be appropriate (Questions 10 and 11). We also think that because of the use of Mathematica™ to handle the equations more efficiently and effectively, students felt that they were provided with enough material to handle the design problem (Question 13). Overall, multidisciplinary design experience was proved to be positive and worthy.

The other concern about forcing the students to use Mathematica™ was proved to be unfounded. Incoming Freshman at Virginia Tech are required to purchase a computer and a software package which includes Mathematica™. However, most of the students in the 1995 senior class had no access to Mathematica™, and some of them did not even know what Mathematica™ was in the beginning of the semester. Therefore, answers to Questions 4 and 5 were split between difficult and easy. However, overall the Mathematica™ experience also proved to be very positive (Questions 1, 2, 3), with strong support for its use in the future (Question 7).

4. Multidisciplinary design curriculum, including the new graduate design program

Undergraduate Program:

Freshman: We have been introducing selected freshman to the multidisciplinary nature of design by having them work with seniors. For three years we have been including two freshmen on each team of seniors in the second semester. This is an NSF-sponsored SUCCEED Project. The freshmen participate fully in the design process, replacing their normal freshman engineering design project with their part of the senior team design project. The freshman instructors usually attend the year-end team design presentations and the freshman present their contribution to their freshman class. We find it works well, although naturally it varies with the student.

Sophomores: Based on the enthusiasm of the freshman for design, we introduced a new course, Introduction to AOE Design, in the fall of 1994. A one-hour elective, this course introduced students to a variety of aspects of design and the aerospace industry. We featured several team building activities and projects. We are still developing multidisciplinary problems for them to tackle. This will be a key element of this class in the future. We found that having a "single-class" sophomore design experience was not nearly as good as having students work with students from other classes, *e.g.*, we need juniors mentoring sophomores. This turns out to be a big part of turning students into engineers. The "cross-class" freshman-senior approach is very effective. Our problem is creating a way to do this often in a traditional engineering education environment.

Juniors: As discussed in Sec. 1, we have started introducing mini-design projects into most of the junior level courses. We hope to start developing a design mentality, and prepare them for senior design. Interviews with students after the senior design class suggested that a better transition was needed. These mini-design projects are typically single-discipline oriented, and we are presently working toward introducing multidisciplinary aspects.

Seniors: The multidisciplinary design experiences available for the seniors have been described above. They include the MDO course available as an elective in the fall semester and participation in the senior design course, where we now use the more focused two-discipline problems regularly. Although we currently use aerodynamic-structural problems based on fuel weight and wing weight, as seen above, we also used engine sizing for the 1994-95 ozone hole replenishment project. We are also developing an aerospace manufacturing course which will illustrate the tradeoff between the design for manufacturability and the complex shaping that may be required to achieve optimum vehicle performance. Another trade will be materials cost compared to weight savings. Taken all together, we believe this will provide students with the broad understanding of multidisciplinary issues required to be effective aerospace engineers in today's environment.

Graduate Program

Student Research Experience: Research in MDO requires working in teams. This includes faculty and students. At least weekly meetings of the entire team are held to ensure good communication. Each student and his advisor also meet individually at least once a week. Faculty have to invest time learning the key issues of each other's area of specialty. The payoff is the development of a broader system design methodology. Each student still produces an individual thesis, yet technical papers are authored by the entire group. After having gone through several generation of students we are learning some lessons. MDO is harder for a student than classical single discipline research. The increased difficulty is almost entirely due to the need to work in teams and maintain good communications, exactly the aspects of education that industry is telling us is needed.[4] Some of the key practical aspects of MDO education are the need to bring new students up to speed on the previous history of our work and the problem of using software written by other students. Control of software versions in a team environment, validation of individual components, and fixing bugs introduced by other students makes MDO more demanding.

The Graduate Design Degree and the NASA MAD Fellowship Program: For several years we had been planning to formalize a graduate program in design. With emerging interest in government, we went ahead and formed the MAD Center. This center provided a focus for identifying and loosely coordinating the numerous multidisciplinary activities which had evolved at Virginia Tech. It also developed a program of study which leads to a certificate in MDO. For more details see **http://www.aoe.vt.edu/mads.html**. The MAD Center won one of the five nationwide Multidisciplinary Design and Analysis Fellowship programs initiated by NASA. The primary purpose of the NASA program is to develop technology to reduce the cost and time of designing and developing an aeronautical system while increasing product quality and reliability. Government studies show that industries need broadly schooled engineers competent in all aspects of design. The fellowship program provides financial support for graduate student fellows for their M.S. and Ph.D. studies in a variety of departments, offering them a combination of academic research and industrial exposure to give them a broad design experience.

An important part of the MAD Center is the Industrial Advisory Board. The research conducted by the fellowship students is based on problems suggested by companies participating in the review board. This is intended to make sure that we are doing research that industry considers relevant. It also enhances university-industry communication. The industrial board also includes representatives from NASA and other government agencies.

Industrial Internship and Academic Program: In addition to performing MAD research, the MAD fellows are required to satisfy the degree requirements of his/her major department and complete MAD related course work which includes optimization, manufacturing and computer aided design courses. A unique feature of the program is the industrial internship opportunity. MAD fellows will spend at least three months, preferably six for Ph.D. students, in industry as an integral part of their graduate program working closely with an industrial partner on a MAD project. Exposure to non-academic design issues in an industrial environment provides an added dimension to the student's graduate program and emphasizes the interaction with industry. It is also a positive addition to the student's record, which will be a valuable asset in the eyes of future employers. Table 4 contains the details of the degree requirements and course offerings for this program.

Concluding Remarks

We have been working with students in MDO for a number of years. Initially the effort was associated with funded research and involved graduate students. Subsequently we have included undergraduates. It has worked out well, and we have developed a number of MDO problems that students can use in courses. Partly as a result of our long-standing interest in MDO, and partly because of increased interest by both government, particularly NASA, and industry, we have established a graduate program in MDO. We expect this program to work well also. Students getting degrees based on research in MDO are getting good jobs.

References

1. Curry, D.T., "Engineering schools under fire," *Machine Design*, Oct. 10, 1991, pp.50-54.
2. Braham, J., "Where are the Leaders?" *Machine Design*, Oct. 10, 1991, pp.58-62.
3. McMasters, J.H., and Ford, S.D., "The [Airplane] Design Professor As Sheepherder," AIAA Paper 90-3259, Sept. 1990.
4. Nicolai, L.M., "Designing a better engineer," *Aerospace America*, April 1992, pp.30-33,46.
5. Evans, D.L., "Integrating Design Throughout the Curriculum," Special Issue, *Engineering Education*, July/Aug 1990.
6. Covert, E.E., "Engineering education in the '90s: Back to the basics," *Aerospace America*, April 1992, pp.20-33,46.
7. Roskam, J., "Facing the crisis in aircraft design education," *Aerospace America*, April 1992, pp.24-27.
8. Johnson, V.S., "Tying It All Together - The NASA/USRA University Advanced Design Program," AIAA Paper 92-1040, Feb. 1992.
9. Dertouzos, M.L., Lester, R.K., and Solow, R.M., and the MIT Commission on Industrial Productivity, *Made in America, Regaining the Productive Edge*, Harper Perennial, 1989.
10. Hoover, C.W., and Jones, J.B., Jr., Ed., *Improving Engineering Design: Design for Competitive Advantage*, National Research Council, National

Academy Press, Washington, 1991.

11. Drezner, J. A., Smith, G. K., Horgan, L. E., Rogers, C., and Schmidt, R., “Maintaining Future Military Aircraft Design Capability,” Rand Report R-4199-AF, 1992.
12. Sobieszczanski-Sobieski, J., “Multidisciplinary Optimization for Engineering Systems: Achievements and Potential,” *Proceedings of an International Seminar, Optimization: Methods and Application, Possibilities and Limitations*, Lecture Notes in Engineering 47, H.W. Bergmann, Editor, Springer-Verlag, Berlin, Germany, 1989, pp. 42-62.
13. Sobieszczanski-Sobieski, J., “Multidisciplinary Design Optimization: An Emerging New Engineering Discipline,” presented at The World Congress on Optimal Design of Structural Systems,” Rio de Janeiro, Brazil, Aug. 2-6, 1993.
14. M. Hutchison, E. Unger, W. Mason, B. Grossman and R. Haftka, “Variable-Complexity Aerodynamic Optimization of an HSCT Wing Using Structural Wing-Weight Equations,” AIAA Paper 92-0212, January 1992
15. M. Hutchison, X. Huang, W.H. Mason, R. Haftka, and B. Grossman, “Variable-Complexity Aerodynamic-Structural Design of a High-Speed Civil Transport,” AIAA Paper 92-4695, September 1992.
16. M.G. Hutchison, E.R. Unger, W.H. Mason, B. Grossman, and R.T. Haftka, “Aerodynamic Optimization of an HSCT Configuration Using Variable-Complexity Modeling,” AIAA Paper 93-0101, January 1993.
17. J. Dudley, X. Huang, R.T. Haftka, B. Grossman and W.H. Mason, “Variable-Complexity Interlacing of Weight Equation and Structural Optimization for the Design of the High Speed Civil Transport,” AIAA Paper 94-4377, Panama City, Fl., September 1994
18. P.E. MacMillin, J. Dudley, W.H. Mason, B. Grossman, and R.T. Haftka, “Trim, Control and Landing Gear Effects in Variable-Complexity HSCT Design,” AIAA Paper 94-4381, Panama City, Fl., September 1994.
19. Brett Malone and W.H. Mason, “Multidisciplinary Optimization in Aircraft Design Using Analytic Technology Models,” AIAA Paper 91-3187, September 1991.
20. B. Malone and W.H. Mason, “Aircraft Concept Optimization Using the Global Sensitivity Analysis and Parametric Multiobjective Figures of Merit,” AIAA Paper 92-4221, August 1992.
21. Jennifer Barnum, Curt Bathras, Kirk Beene, Michael Bush, Glenn Kaupin, Steve Lowe, Ian Sobieski, Kelly Tingen, and Douglas Wells, “Advanced Transport Design Using Multidisciplinary Design Optimization,” AIAA Paper 91-3082, Sept. 1991.
22. W.H. Mason, “Analytic Models for Technology Integration in Aircraft Design,” AIAA Paper No. 90-3262, September 1990.
23. Sobieszczanski-Sobieski, J., “Sensitivity of Complex, Internally Coupled Systems,” *AIAA Journal*, **28**, No. 1, January 1990, pp. 153-160.
24. Vanderplaats, G., “Automated Optimization Techniques for Aircraft Synthesis,” AIAA Paper 76-909, Sept., 1976.
25. Wampler, S.G., Myklebust, A., Jayaram, S., and Gelhausen, P., “Improving Aircraft Conceptual Design — A PHIGS Interactive Graphics Interface for ACSYNT,” AIAA Paper 88-4481, Sept. 1988.
26. Jayaram, S., Myklebust, A., and Gelhausen, P., “ACSYNT - A Standards-Based System for Parametric Computer Aided Conceptual Design of Aircraft,” AIAA Paper 92-1268, Feb. 1992.
27. Mason, W. H., “Aircraft Design Course Computing Systems Experience and Software Review,” Aerospace Engineering Division, ASEE Annual Conference, Anaheim, CA, June 1995.
28. Goodrich, K. H., Sliwa, S. M., and Lallman, F. J., “A Closed-form Trim Solution Yielding Minimum Drag for Airplanes with Multiple Longitudinal Control Effectors,” NASA TP-2907, May 1989.

Table 1.
Computer Codes Available for use in Senior Design Projects

Aerodynamics		
*	VLM4997	John Lamar's subsonic vortex lattice program
*	LIDRAG	Span "e" determination for induced drag
*	FRICTION	Skin friction calculation
	GRUMFOIL	2D viscous airfoil analysis for subsonic/transonic flow
	AWAVE	Harris wavedrag program
Structures		
*	ELAPS	Equivalent plate analysis of aircraft wing structures (from NASA Langley)
Flight Controls/Handling Qualities		
*	Digital DATCOM	Stability derivative estimation
	MacHoneyX	Control system design (Honeywell's public domain control system design software)
Propulsion		(version 2 of the AIAA engine programs by Jack Mattingly)
	ONXv2	Engine design for specified conditions
	OFFXv2	Analysis of a designed engine at off design conditions
Mission Performance		
	BASIC.PERF	Powers' BASIC Aircraft Performance program (in BASIC)
	MISS1	USAF Mission program using OFFX, also by Mattingly
	FLOPS	can be used for mission analysis
*	ACSYNT	" " " "
Aircraft Sizing		
	FLOPS	NASA Langley aircraft sizing program
*	ACSYNT	NASA Ames aircraft sizing program
Design Layout		
*	ACSYNT/VPI	graphics, CAD style geometry development for conceptual design, including analysis of ACSYNT results
	CADAM	standard CAD system available for configuration design
Optimization		
	COPES/CONMIN	Vanderplaats' engineering synthesis control and optimization
*	STORM A linear programming code used in VPI optimization classes	

* denotes codes actually used by the MDO group

Table 2
MDO Homework problem
AOE/ESM 4084, Homework Assignment 1
Due 2:00 pm, Thursday, September 8, 1994

PROBLEM

The takeoff gross weight of an aircraft, W_{to}, is the sum of the wing weight, W_{wing}; fuel weight, W_{fuel}; engine weight, W_{eng}; a fixed weight, W_{fix}, which includes structural weight (excluding the wing) and the systems weight; cargo weight, W_{cargo}; and the fuel weight used for the climb, W_{fclm}.

$$W_{to} = W_{wing} + W_{fuel} + W_{eng} + W_{fix} + W_{c\arg o} + W_{fclm}$$

The wing weight may be calculated from

$$W_{wing} = 0.0051\, S_w^{0.649}\, S_{csw}^{0.1}\, \frac{AR^{0.5}\left(NW_{to}\right)^{0.557}(1+\lambda)^{0.1}}{(t/c)^{0.4}\cos\Lambda}$$

where S_w is the wing area, S_{cws} is the area of the wing mounted control surfaces, *AR* the aspect ratio, *t/c* the wing thickness to chord ratio, *N* ultimate load factor, λ taper ratio, and Λ sweep angle. The fuel weight for cruise can be found from the Brequet range equation

$$W_{fuel} = \left(W_{to} - W_{fclm}\right)\left(1 - e^{-\frac{R\,sfc}{V\,0.5925(L/D)}}\right)$$

where *R* is the range (in nautical miles), *sfc* specific fuelconsumption, *V* cruise speed (in ft/sec), and *L/D* lift to drag ratio. The lift coefficient for cruise can be calculated from

$$C_L = \left(W_{to} - W_{fclm}\right)/\left(0.5\rho V^2 S_w\right)$$

The drag coefficient is composed of three components

$$C_D = C_{D_0} + C_{D_{wave}} + \frac{C_L^2}{\pi ARE}$$

where *E* is the Oswald efficiency factor, *E* = 0.8, and

$$C_{D_0} = 0.0045 + 0.0058[1 + 1.8(0.75x0.66(t/c)) + 100(0.75x0.66(t/c))^4] + 0.0032\,\frac{15000}{S_w}$$

$$C_{D_{wave}} = 20\left(M - M_{crit}\right)^4/\cos^4\Lambda \qquad M_{crit} = M_{DD} - (0.1/80)^{1/3}$$

and

$$M_{DD} = \frac{0.9}{\cos\Lambda} - \frac{(t/c)}{\cos^2\Lambda} - \frac{C_L}{10\cos^3\Lambda}$$

Table 2 (concluded)

The engine weight, W_{eng}, is typically calculated based on required thrust and the thrust to weight ratio of the propulsion system chosen for the aircraft. In this problem we will assume the engine weight to be fixed at W_{eng} = 4x7500 lb (four engines). The fixed weight and the fuel weight for climb are typically related to takeoff weight of the aircraft. For the present problem we have $W_{fix} = 0.2\ W_{to}$ and $W_{fclm} = 0.02\ W_{to}$.

Use Mathematica to plot the variation of the cargo weight W_{cargo} as a fuction of

i) aspect ratio, $4 < AR < 24$

ii) wing area, $3000 < S_w < 10000$

iii) Mach number, $0.5 < M < 0.9$

iv) sweep angle, $0° < \Lambda < 40°$

(by fixing all other variables to their baseline values) for the following two baseline design configurations.

	design-1	design-2
aspect ratio, AR	7.0	22.65
wing area (ft2), S_w	3800	3957
Mach number, M	0.78	0.61
sweep angle (deg), Λ	21.0	1.0
thickness ratio, t/c	0.1	0.18
taper ratio, λ	0.1	0.27
takeoff weight, W_{to}	449000	423600

For the wing under consideration, $S_{cws} = 0.1\ S_w$, $N = 4.5$, $R = 3000$ nm, $sfc = 0.640$. Also use $\rho = 0.0008$ slug/ft^3, and the speed of sound to be 980 ft/sec.

Table 3.
Survey of Students in the MDO Course

A) Mathematica™ Experience

1) Use of Mathematica™ notebook for delivering lectures was

a) very useful	[9]	c) not useful	[-]
b) somewhat useful	[5]	d) did not make a difference	[-]

2) Use of Mathematica™ for demonstrating concepts was

a) very useful	[10]	c) not useful	[1]
b) somewhat useful	[3]	d) did not make a difference	[-]

3) Use of Mathematica™ for solving homework problems was

a) very useful	[10]	c) not useful	[-]
b) somewhat useful	[4]	d) did not make a difference	[-]

4) Having access to Mathematica™ was

a) very difficult	[1]	c) somewhat easy	[4]
b) somewhat difficult	[5]	d) easy	[4]

5) Learning how to use Mathematica™ was

a) very difficult	[1]	c) somewhat easy	[5]
b) somewhat difficult	[7]	d) easy	[1]

6) Enough material was provided to enable the students to learn Mathematica™

a) agree	[5]	c) somewhat disagree	[3]
b) somewhat agree	[6]	d) disagree	[-]

7) Use of Mathematica™ in the future should be

a) increased	[5]	c) decreased	[2]
b) kept at the same level	[7]	d) removed	[-]

B) Multidisciplinary Design Optimization (MDO) Experience

9) The multidisciplinary wing-design problem made the homework problems

a) too difficult	[1]	c) no different	[4]	e) easy	[-]
b) somewhat difficult	[7]	d) somewhat easy	[2]		

10) Use of the wing-design problem for homework problems

a) too frequently	[5]	b) just about right	[9]	c) too little	[-]

11) Use of the same problem repeatedly for demonstrating different concepts was

a) very useful	[2]	c) not useful	[1]
b) somewhat useful	[9]	d) did not make a difference	[2]

12) You had the background information needed to solve the wing-design problem

a) agree	[7]	c) somewhat disagree	[2]
b) somewhat agree	[5]	d) disagree	[-]

13) Enough material was provided to enable you to solve the wing-design problem

a) agree	[9]	c) somewhat disagree	[-]
b) somewhat agree	[5]	d) disagree	[-]

14) This course introduced you to multidisciplinary design optimization

a) agree	[10]	c) somewhat disagree	[2]
b) somewhat agree	[2]	d) disagree	[-]

15) The topic of Multidisciplinary Design Optimization was important for you

a) agree	[9]	c) somewhat disagree	[-]
b) somewhat agree	[4]	d) disagree	[1]

Table 4
Requirements for MAD Fellows

MAD fellows are students enrolled in the MAD center certificate program. The student needs to satisfy the requirements for a degree in one of the disciplinary programs, e.g., AOE or ESM, and the following additional requirements:

1. Perform MAD research for a thesis or a dissertation.
2. Complete MAD related course work.
3. Spend at least three months (preferably six for Ph.D. students) in industry working on a MAD project.

These three requirements are fulfilled according to the following guidelines:

1. MAD research:

The student will fill out a form listing the research topic, the disciplines involved, and explaining why the research is multidisciplinary in nature and why it related to the design of advanced vehicles. The topic will need to be signed by the student's thesis or dissertation committee and the MAD center director. This form will be completed at the same time and accompanied by the student's program of study.

2. MAD course work:

An MS student must complete courses in at least two of the following four categories: Optimization, manufacturing, systems engineering and economic analysis, and computer aided design. A Ph.D. student must take at least one course in three of the four categories. The list of currently approved courses for each category is given below.

3. Industrial internship:

The student's dissertation committee and the MAD center director will need to approve the choice of the company for industrial internship to insure that the internship is likely to significantly contribute to the student's exposure to non-academic design issues.

COURSE OPTIONS CURRENTLY AVAILABLE

Optimization Courses

AOE 4084 (ESM 4084) ENGINEERING DESIGN OPTIMIZATION

Use of Mathematical programming methods for engineering design optimization including linear programming, penalty function methods, and gradient projection methods. Applications to minimum weight design, open-loop optimum control, machine design, and appropriate design problems from other engineering disciplines.

AOE 5064 (ESM 5064) STRUCTURAL OPTIMIZATION

Structural optimization via calculus of variations. Application of techniques of Mathematica™l programming to optimize trusses, beams, frames, columns, and other structures. Sensitivity calculation of structural response. Approximation techniques and dual and optimality criteria methods. A background in optimization is necessary.

AOE 5244 OPTIMIZATION TECHNIQUES

Ordinary minimum problems with constraints. The classical multiplier method, descent methods, and quasi-Newton methods. Optimal control and the maximum principle. Second-order necessary conditions. Singular control. Continuous gradient methods, conjugate gradients.

MSCI 5404 MANAGEMENT SCIENCE

Study of selected topics in management science as they apply to managerial decision making. Topics include resource allocation using linear programming, transportation and assignment models, network models for planning and scheduling, queuing models for waiting line analysis, and an introduction to simulation modeling and analysis. Use of the computer for problem analysis and solution is emphasized.

Table 4, Requirements for MAD Fellows (Continued)

ISE 5405 OPTIMIZATION

Linear programming, modeling, assumptions, and structural properties; primal, dual, and primal-dual simplex algorithms; convergence and implementation issues; duality theory; sensitivity and parametric analysis; linear multi-objective and goal programming, introduction to integer, dynamic, and nonlinear programming.

ISE 5406 OPTIMIZATION

Nonlinear programming theory and algorithms: convex sets and functions, generalized convexity; and theorems of the alternative, constraint qualifications, necessary, and/or sufficient optimality conditions.

MSCI 5444 ADVANCED MANAGEMENT SCIENCE

Study of advanced topics in management science, with emphasis on topics not covered in MSCI 5404. Topics presented include advanced topics in linear programming, duality and sensitivity analysis, integer programming, quadratic programming, goal programming, and dynamic programming, Emphasis is placed on use of the computer for problem analysis and solution. Term project included.

Computer Aided Design Courses

ME 5604 COMPUTER-AIDED DESIGN I

Participants will study topics fundamental to the creation of computer-aided design software including CAD hardware, standard graphics (GKS, PHIGS), mathematics of 3-D modeling, and 3-D CAD support software. Applications programs will be developed which use graphics support software or interface to a commercial 3-D CAD system.

ME 6604 COMPUTER-AIDED DESIGN II

Participants will study topics related to rendering computer images such as shading and lighting models and color transformations. Methods of geometric modeling for curves, surfaces and solid models will be studied and applied to computer-aided design problems.

AOE 5074 COMPUTER-AIDED DESIGN OF VEHICLE STRUCTURES

Methodology of rationally-based, computer-aided optimum structural design, Reliability aspects. Advanced aspects of finite element analysis for large then wall structures. Modes of failure at member, multi-member and overall level for large thin wall structures. Other limit states. Optimization methods. Principles of computer-aided design and sample applications.

ESM 5984 SCIENTIFIC VISUAL ANALYSIS WITH MULTIMEDIA (special study)

Classical and advanced methods of visual data analysis are studied with scientific applications and interactive multimedia presentation of results. Examples of scientific visual insight, are studied and new visual methods are created with the aid of computer graphics. Visual
data analysis of numerical, experimental, or analytical results are used to study gradients, function-extraction, chaos, second and fourth order tensors, and molecular synthesis with applications in solid-fluid mechanics, dynamics, and material science. Special topics such as data sonification and virtual reality are discussed in context with scientific applications. The final class project emphasizes how interactive graphical methods can be insightfully used within the scientific application and for final presentation.

Table 4, Requirements for MAD Fellows (Concluded)

Systems Engineering Courses

ENGR 5004 THE SYSTEMS ENGINEERING PROCESS

Development and implementation of the systems engineering process commencing with the identification of requirements (i.e., a consumer need) and extending through requirements allocation, system and functional analysis, synthesis and optimization, the identification of a specific system configuration, and system test and evaluation. The process includes the integration of performance factors, reliability and maintainability, human factors, logistic support, effectiveness, life cycle, and other factors necessary in systems development.

ENGR 5104 APPLIED SYSTEMS ENGINEERING

Identification of the role of systems engineering -- solving problems involving technology in the context of the society and the environment in which they exist using systems methodologies of current and potential usefulness in public and private decision making.

ISE 4224 ADVANCED ENGINEERING ECONOMY

Economic models involved in the prediction and control of capital expenditure decisions. This course extends the basic concepts of engineering economy and industrial cost control and integrated the techniques of classical economic theory, decision theory, and operations research.

Manufacturing Courses

ISE 4264 INDUSTRIAL AUTOMATION

A survey of technological and economic factors pertaining to industrial automation. Examination of components commonly employed in automation systems, their aggregation, and related production process design.

ISE 5204 MANUFACTURING SYSTEMS ENGINEERING

Conceptual models of manufacturing, process, and service organizations for various operational levels are presented. Functional activities and interrelationships are defined for each type of manufacturing model. Typical objectives and operating constraints are identified for functional activities, particularly production planning/control, materials management, facilities design/material handling.

ISE 5234 MANUFACTURING COSTS AND PRODUCTION ECONOMICS

Concepts and techniques of analysis for evaluating the life cycle costs and benefits of manufacturing assets and production systems. International economic competition, design and production economics, strategic implications of capital investment, investment decision analysis, economic appraisal and control, and the economic retirement of manufacturing assets.

ISE 5304 DIGITAL COMPUTERS IN MANUFACTURING SYSTEMS CONTROL

An introduction to computer software and hardware concepts as applied to manufacturing systems interfacing control. Includes microprocessor architecture, related hardware devices, software systems concepts in data acquisition and control. manufacturing applications of computers, and computer integration for manufacturing systems control.

ESM 5204 COMPOSITE MANUFACTURING

Fundamentals of polymeric matrix composite manufacturing. Mathematica™l models of curing, consolidation, and void formation processes are studied. Prepregging methods and effects of processing on mechanical properties are discussed. Introduction to commonly used manufacturing processes. Laboratory demonstrations.

AOE AEROSPACE MANUFACTURING (course being developed)