

## **ENGINEERING DESIGN AND RAPID PROTOTYPING: A REWARDING CAD/CAE/CAM AND CDIO EXPERIENCE FOR UNDERGRADUATES**

**Prof. O. L. deWeck<sup>1</sup>, Prof. I.Y. Kim<sup>2</sup>, C. Graff<sup>1</sup>, W. Nadir<sup>1</sup>, A. Bell<sup>1</sup>**

<sup>1</sup> Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA 02139 USA

<sup>2</sup> Department of Mechanical Engineering, Queen's University, Kingston, Ontario K7L 3N6, Canada

### **ABSTRACT**

This paper presents the second offering of a new undergraduate design and rapid prototyping course in the Department of Aeronautics and Astronautics at MIT. The course combines design theory, lectures, and hands on activities to teach the design stages from conception to implementation and testing. Activities include hand sketching, CAD, CAE, CAM, design optimization, rapid prototyping techniques, and performance testing. The learning objectives, pedagogy, required resources and instructional processes, as well as results from the latest implementation of the course and student assessments are discussed. A review of the previous year's assessments and a short project description is also included. A key pedagogical insight from this course is that design iterations are not to be interpreted as error correction or rework, but as an essential part of a sound engineering process.

### **INTRODUCTION**

With the implementation of CDIO [conceive-design-implement-operate] throughout the undergraduate education in the Department of Aeronautics and Astronautics at MIT, various student surveys have shown that one of the objectives of combining fundamental theory with practical applications was lacking. There is a desire for specific training in modern design methods and tools, such as state-of-the-art CAD/CAE/CAM technology, and integrating design optimization. Students have suggested the addition of a short and intense course within the IAP (independent activities period) in design and rapid prototyping, combined with design optimization. The specific reference from the student survey is paraphrased here:

*"The CDIO [conceive-design-implement-operate] initiative has been well received by undergraduates, who have thoughtful suggestions for improvements. Some feeling of imbalance between fundamentals and other skills. Offerings in CAD/CAM, machining, fabrication desired."*

The intent of this course is to respond and help fill this perceived gap, combine multiple disciplines to give students an introduction to design optimization, and offer exposure to design and manufacturing tools. The 6-credit-unit IAP course takes students through the conception, design, and implementation of a single, simple sub-system or component of a vehicle during a period of 4 weeks. This course supports the learning objectives of the CDIO (Conceive-Design-Implement-Operate) initiative [1,2,3] and attempts to use the latest technologies in computer

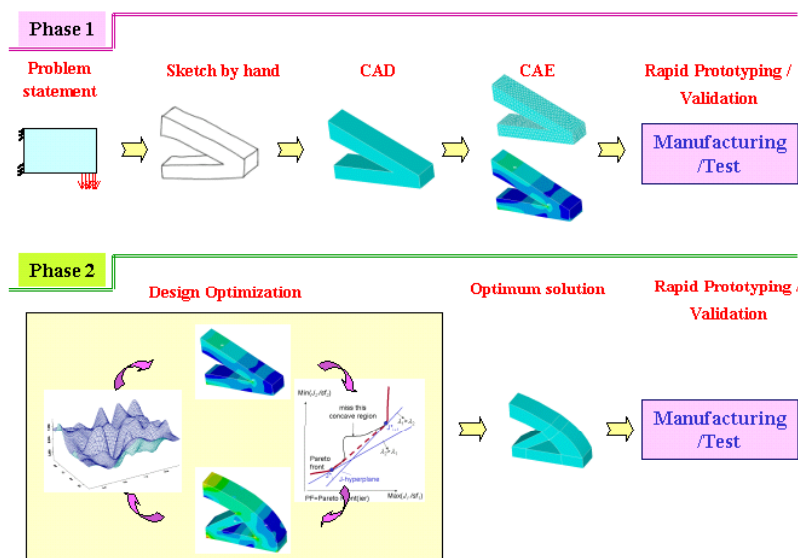
aided design, analysis, manufacturing, and rapid prototyping to achieve these goals. Also, this course attempts to expose students to the engineering design process, as well as encouraging optimization and multi-disciplinary thinking. The novelty of this course lies in the combination of rapid prototyping and manufacturing, with engineering design and optimization in order to demonstrate the complementary capabilities of computer tools and human ingenuity during the design process. The overall learning objective of this activity is for students to develop a holistic view of and initial competency in engineering design by applying a combination of human creativity and modern computational methods and tools to the synthesis of a complex structural component.

This goal can be mapped onto the following learning objectives of the CDIO syllabus [2]:

- (1) Core Engineering Fundamental Knowledge: solid mechanics & materials
- (2) Advanced Engineering Fundamental Knowledge: computational techniques
- (3) Engineering Reasoning and Problem Solving: modeling
- (4) Personal Skills and Attitudes: creative thinking
- (5) Conceiving and Engineering Systems: modeling systems and ensuring goals can be met
- (6) The Design Process: execute appropriate optimization in the presence of constraints
- (7) Implementing: hardware manufacturing process
- (8) Implementing: test, verification, validation, and certification

## COURSE DESCRIPTION

The overarching goal of the course is to provide the students with an opportunity to conceive, design, and implement products quickly and effectively, using the latest rapid prototyping methods and CAD/CAE/CAM technology. This is meant to be an intense and satisfying experience that emphasizes the overall chain of design steps shown in Figure 1.



**Figure 1:** Engineering Design and Rapid Prototyping: course pedagogy

The course was offered for two iterations, with the first class during IAP (Independent Activities Period) of January 2004, and the second class during IAP of January 2005. IAP is a 4-week long term at MIT that offers students the chance to explore other classes and extracurricular activities than those offered during the normal spring and fall semester schedule.

## COURSE PEDAGOGY AND CONCEPT

The course is structured in two phases, with fundamental engineering design principles and procedures introduced and reviewed during the first phase, and application and implementation of the design during the second phase.

In the first phase, the students are presented a design problem with solution neutral requirements and constraints. For IAP 2004, the problem was purely structural; whereas for IAP 2005 the design problem included structural and aerodynamics disciplines. A creative design process of hand sketching is followed by computer aided design (CAD) and analysis (CAE). The analysis included both finite element methods and computational fluid dynamics. This initial design concludes Phase One.

The second phase takes the initial Phase One design, and looks to improve the solution via design optimization. The first manual solution is used as a baseline condition for the design optimization step. The goal is for students to conduct design optimization using either commercial or faculty-provided software. The optimum solution obtained is modeled again in CAD, analyzed through the CAE tools, and then fabricated using CNC (computer numerically controlled) equipment. The optimized component is then compared with the original, and conclusions are drawn from analysis. Students were encouraged to implement formal design optimization during their design process, either through purely manual iterations or through software, but without the benefit of initial design testing and verification.

The course concludes with student presentations culminating in a “Critical Design Review”, which includes results from testing of the initial and optimized designs. This side-by-side comparison between designs and student teams helps produce several educational insights:

- (1) Understanding of the predictive accuracy of CAE modeling versus actual test results
- (2) Understanding of the relative improvement that computer optimization can yield relative to an initial, manual solution
- (3) Illustration of the capabilities and limitations of the human mind and digital computer during design and manufacturing

## COURSE FLOW

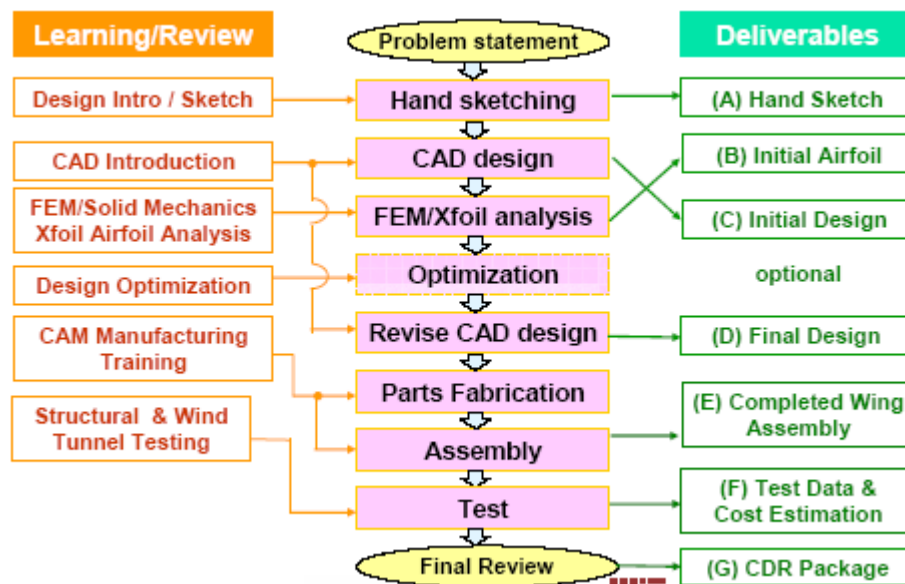


Figure 2: Flowchart of Engineering Design and Rapid Prototyping class

The course plan starts by exposing the students to the design process, its phases, and the importance of properly formulated requirements. An introduction to state-of-the-art CAD/CAE/CAM environments is given during the first week. Initial hands-on activities include hand sketching, creating engineering drawings, and CAD Modeling. Due to the time limitations of the IAP course, compromises have to be made with respect to the breadth and depth of some of the topics that are covered. Emphasis is placed on successfully completing the various steps of the design process, rather than understanding all the details of the methods and tools used along the way. Assumptions outlined in the Project Description limit the complexity of this undertaking in order to avoid overwhelming the students and to ensure that they focus on the learning objectives. Figure 2 shows a flowchart of the main class activities (center), student deliverables (on the right side), and learning/review activities (on the left side).

Figure 3 shows the detailed course schedule for IAP 2005. Each class consists of two lectures on theory (2 hours) directly followed by a hands-on activity period where the theory is immediately applied (2 hours). The first five lectures constitute the bulk of Phase One, with Phase Two beginning with the optimization lecture.

Session Dates	Lecture Topics	Hands-On Activities	Deliverables Due	Lab/Software
1 – Tues, Jan 4 1-5pm	<b>L1: Introduction to Design (de Weck)</b>  <b>L2: Hand Sketching (Wallace)</b>	Form teams, Sketch initial designs by hand, Tour the facilities		33-218 Design Studio, Machine Shop, Hangar, Wind Tunnel.
2 – Thu, Jan 6 1-5pm	<b>L3: Airfoil analysis, Xfoil tutorial (Drela)</b>  <b>L4: CAD Modeling, Solidworks tutorial (de Weck)</b>	Choose initial airfoil, Rough sizing, Hand calculation of lift, drag and mass, Initial design of support structure.	<b>(A) Hand sketch of conceptual design (1 page)</b>	33-218 Xfoil/Profil Solidworks
3 – Tue, Jan 11 1-5pm	<b>L5: Computer Aided Engineering (CAE) – FEM (de Weck)</b>  <b>L6: Design Optimization (de Weck)</b>	Start FEM modeling. Refine loads analysis.  Intro to aero-structural interactions and optimization. Refine initial design.	<b>(B) Initial 2-D airfoil design and analysis (2-pg memo)</b>	33-218 Xfoil/Profil Solidworks Cosmos Matlab
4 – Thu, Jan 13 1-5pm	<b>L7: Guest Lecture: Bill Taylor (ArvinMeritor)</b>  <b>L8: Intro to CAM. (de Weck, Col. Young)</b>	Introduction to water-jet cutter, and foam cutter. (Col. Young,.) Lab work, Start manufacturing.	<b>(C) Initial 3-D Solidworks model. (2-pg memo)</b>	33-218 OMAX Gelb Lab Waterjet Foam cutter
5 – Tue, Jan 18 1-5pm	<b>L9: Structural Testing (de Weck)</b>	Continue building wing, manufacture support structure, perform assembly	<b>(D) Final 3-D CAD model, incl. airfoil &amp; FEM analysis (4-pg report)</b>	33-218 Gelb Lab Hangar Wind Tunnel
6 – Thu, Jan 20 1-5pm	<b>L10: Windtunnel Testing (Perdichizzi)</b>	Structural load test	<b>(E) Completed wing assy (1-pg report on mfg).</b>	33-218 Gelb Lab Hangar
Fri, Jan 21	Testing	Wind tunnel test		Wind Tunnel
Mon, Jan 24	Testing	Wind tunnel test		Wind Tunnel
7 – Tue, Jan 25	No class	Prepare final presentation	<b>(F) Final testing report. (2- pg report).</b>	33-218
8 – Thu, Jan 27 1-5pm	<b>L11: Guest Lecture: Dr. Sobieski, NASA LaRC</b>  <b>Critical Design Review (CDR)</b>	Give final presentations; Announce winner of design competition	<b>(G) CDR Presentation (max 7 slides), reflective memo (1 page)</b>	Bldg. 9 Kauffman/Ford Room

**Figure 3:** Flowchart of Engineering Design and Rapid Prototyping class

Due to time constraints, two full iterations through the design process were not possible; thus Phase Two lectures were minimized, and fabrication and testing of the Phase One components emphasized. Students were also encouraged to incorporate design optimization during their design phases, albeit without the knowledge gained from initial testing. Should there be more time overall for the course, Phase Two classes and deliverables can be easily implemented as they generally take less time, as much of the upfront software and hardware learning has already taken place. Two guest lectures provide the students with opportunities to learn about current practices and challenges in industry.

The main difference between IAP 2004 and IAP 2005 was the number of days of class per week. For IAP 2004, there were 3 days per week of classes, and the class divided into 1.5 hours of lecture and 1.5 hours of hands-on activity. The first seven sessions (2.5 weeks of IAP) consisted of Phase 1, and the remaining four made up Phase 2. Given the simpler project and manufacturing aspects of IAP 2004, the students were able to complete two full iterations (from design to manufacturing and testing) during the phases.

## **STUDENT TARGET POPULATION**

A small number of students are preferable, due to the laboratory oriented class structure, and the inherent limits of the Design Studio and machine shop. For IAP 2004 the class was limited to 18 students (broken down into 9 teams of two students each), whereas for IAP 2005 the class size was further reduced to 13 students (broken down into 6 teams). The target level were seniors (4<sup>th</sup> year) and juniors (3<sup>rd</sup> year) who already have basic knowledge of mechanics, engineering mathematics, and design, although a number of sophomore (2<sup>nd</sup> year) students who took the course were sufficiently able to handle the course work. The course is targeted primarily to undergraduate students with special emphasis on Aerospace and Mechanical Engineering.

This course is offered as an elective and seeks to attract students who want to:

- (1) Experience the conceive-design-implement-operate process for a simple sub-system or single complex component using the latest CAD/CAE/CAM technology.
- (2) Understand the subtleties of complementary human design abilities and computer strengths in optimization.
- (3) Understand the predictive accuracy of CAE modeling versus actual laboratory test results.
- (4) Obtain 6 units of credit without imposing additional scheduling constraints during the regular semesters.

## **FACILITIES AND RESOURCES**

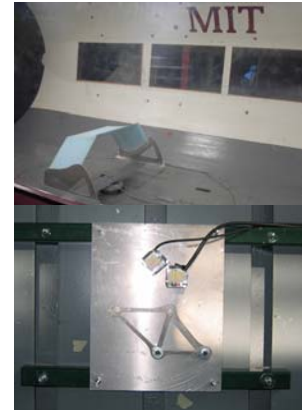
All the lectures and computer-based hands-on activities are performed in a Design Studio (Fig. 4a). This concurrent engineering facility is comprised of 14 networked CAD/CAE workstations that are used for complex systems design and optimization. All software was installed and running on these workstations. The SolidWorks and CosmosWorks package was used for the CAD design and the finite element analysis, respectively. A 2-D airfoil analysis program called XFOIL was used for the computational fluid dynamics analysis, and Matlab as a general computational program. An abrasive waterjet cutter with OMAX CAM software and a foam cutter CNC machine were used for rapid prototyping in the department's machine shop (Fig. 4b). Full-scale testing was conducted in the MIT Wright Brothers Wind Tunnel facility for the IAP 2005 project. Full-scale testing was conducted in the Gelb Laboratory Hangar facility for the IAP 2004 project.



(a) Design studio



(b) Abrasive water-jet cutting machine and foam cutter machine

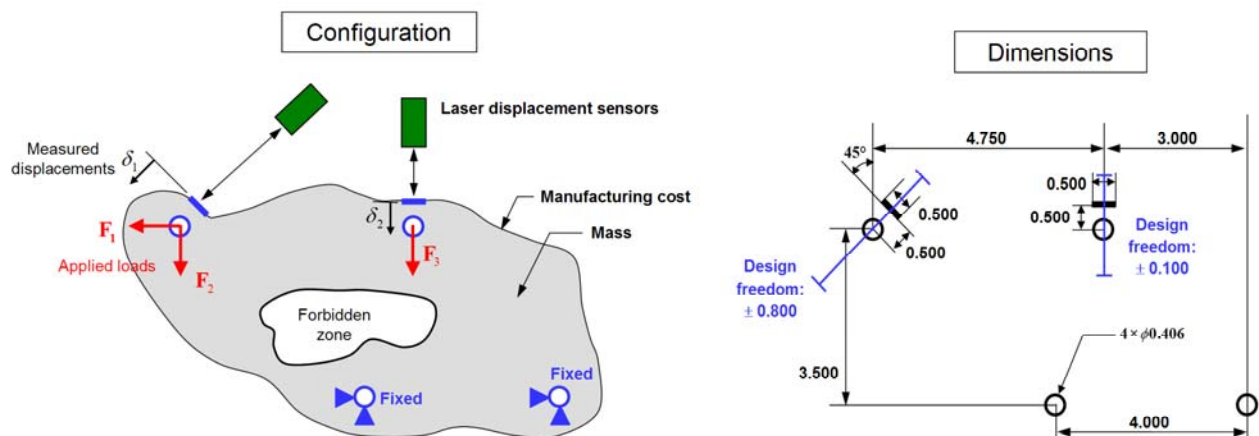


(c) Wright Brothers Wind Tunnel Facility, and Fixture for Testing (test article installed)

**Figure 4:** Design studio, abrasive waterjet, and fixture for testing

## PROJECT DESCRIPTION

For IAP 2004, the initial design project was limited to a single structural component with medium complexity (some boundary conditions, one single-load case, some functional surfaces, and forbidden zones given). The maximum part dimensions are approximately 12" x 12" x 0.5", and made from a single sheet of aluminum. No assemblies, machines, or mechanisms were produced. Due, partly in response to the students wishes, the part complexity was increased for IAP 2005, and can be modified in future years as we learn more about feasibility, student ability, and time constraints. The design task was limited to two dimensions, which simplified hand sketching and CAD modeling, as well as construction. For IAP 2004 the design project was to model and build a scaled down bicycle frame.



**Figure 5:** Configuration and dimensions of the design requirement

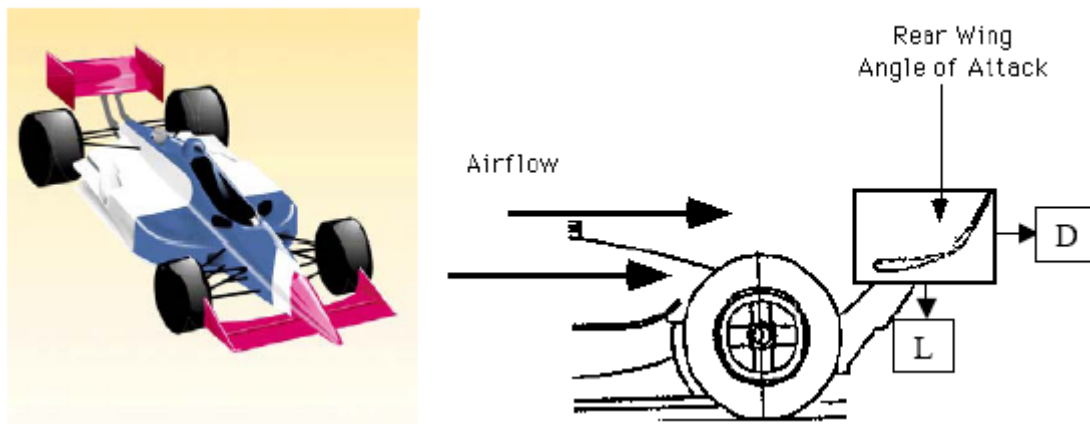
Figure 5 shows the configuration and dimensions associated with the design requirement of the project. The lower two holes are fixed, and three loads  $F_1$ ,  $F_2$  and  $F_3$  are applied to the two upper holes (Fig. 5a). The holes represent the location of the pedals and the



rear axle, and the forces represent the fork and saddle loads. A fixture with two laser sensors was fabricated and used for structural testing; see Figure 4 (c), in order to obtain measurements of the displacements,  $\delta_1$  and  $\delta_2$ .

The class had nine teams of two students each, with every team carrying out a surrogate bicycle frame design for a different hypothetical market segment. The nine market segments were as follows: Family economy, Family deluxe, Cross over, City bike, Racing, Mountain, BMX, and Acrobatic, and Motor bike. The first four represented the consumer division, the next four represented a specialized division, and the last represented the motor division that had special requirements. During the last week of the course, the students visited a leading, local bicycle frame manufacturer [8], where they saw first hand that designing products based on the needs of differentiated market segments is very relevant in the real world. Load magnitude, design requirements, and design priorities vary according to the market segment.

For IAP 2005, the faculty and TAs looked into a more complex project, marrying structural design to aerodynamics. A major competitive element in race car design is efficient aerodynamic design [1,2,3]. Team designers consider aerodynamic efficiency to be the most important element in developing a competitive race car. Roughly speaking, aerodynamic design is concerned with two primary elements: reducing drag ( $D$ ) and increasing downforce (negative lift,  $L$ ). The principles, which allow aircraft to fly, are also applicable in car racing; however the main difference is that the wing or airfoil shape is mounted upside down producing downforce instead of positive lift (Fig.6, right). Downforce is necessary in maintaining high speeds through the corners and forces the car to the track. Although actual race car design includes complex interactions between the aerodynamics of the front wing, rear wing and the main chassis, in this project we focused on the isolated design of one component of the race car: the rear wing.



**Figure 6:** Project Description and Scoping

The project for IAP 2005 was for the students to design and build a wing section, its supports, and then test the wing in the wind tunnel. The students were given boundary conditions and a nominal operating condition. The objective was to maximize downforce, while minimizing weight and drag, using the following objective function:

$$\text{maximize } [ F = L - 3 \cdot D - 5 \cdot W ] \quad (1)$$

Where:

$L$  = measured downforce (negative lift) at specified speed [N]

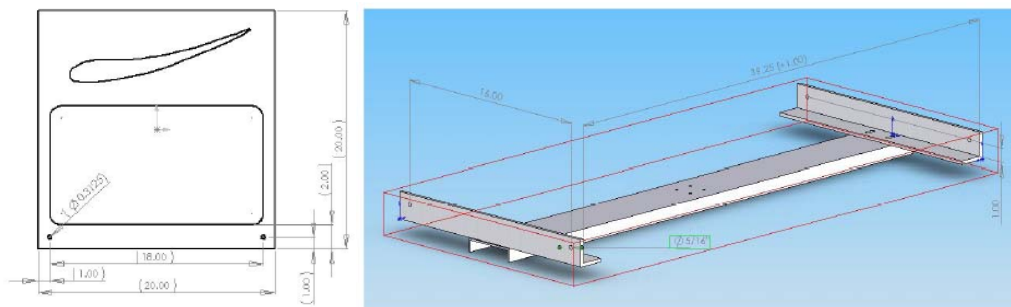
$D$  = measured drag at specified speed [N]

$W$  = total weight of the assembly (not including test fixture) [N]

The nominal speed is 60 mph.

The physical boundary constraints roughly encompass a box, with the maximum design envelope for the wing and its support structure being 20" x 20" x 40" (width, height, span). The wing model can be created as an extrusion of a 2D wing section, thus limiting the aerodynamic analysis to 2D section airfoils, well within the scope of even sophomore (2<sup>nd</sup> year) students. There will be no taper or dihedral requirement, thus simplifying the analysis further and allowing for easier manufacturing using the CNC foam cutter. However, taper or dihedral are not explicitly forbidden in the final design.

The design task also includes developing an attachment method of the wing to the supports and load cell, with the support fixture attachment points to the wing strut at pre-defined points. This will allow quickly mounting, testing, and comparison of wing designs produced by different teams. An example wing support strut, with the required dimensioning for the attachment points along the bottom is in Figure 7. To the right is a view of the test fixture to which the endplate/struts will attach to. This test fixture also has dimensioning constraints.



**Figure 7:** Configuration and dimensions of the design requirement

One of the implicit goals of this design task was to illustrate the problems and complexities of multiple part assemblies, and to give students a better understanding of the issues involved in designing and building interfaces between parts. It was generally found that most students can design and analyze a single part very well, but had difficulties grasping the concept of specifying attachment points, methods, and even considering loads at the interface points. Limiting the actual parts to 2-D extrusions made hand sketching and CAD modeling easier, while still allowing 3-D design freedom and structural analysis.

These brackets are the boundary conditions for the support struts, which the student teams will design. The design of the support strut to the wing is left open to the student design teams. The material available for students for the support struts/structure is either:

- (1) 24 x 24 inch Aluminum 6061 plate, 0.125 inches thick
- (2) 24 x 24 inch Aluminum 6061 plate, 0.25 inches thick.

One of the considerations is that the 1/4-inch thick Aluminum plate is roughly 3 times as expensive as the 1/8-inch thick plate, and this will have to be taken account for in the student's manufacturing reports and cost estimations.

The attachment of the wing(s) to the support structure end plates can be done in a variety of methods, such as epoxy, using a tube as a support strut, or screws. The foam wings were fiber-glassed to minimize deflection. Students had to make an informed design decision with regards to fiber-glassing, using a support rod or other innovative interface methods.

All final designs had to be accompanied by a cost estimate, which included an estimate of both labor (hours worked) as well as material costs. A standard form was provided separately. Aside from attempting to optimize the objective function, student teams also investigated the performance of the wing over the entire wind speed range up to  $v_o$ , look into the center span deflection, mass of wing, mass of support structure and natural frequency of



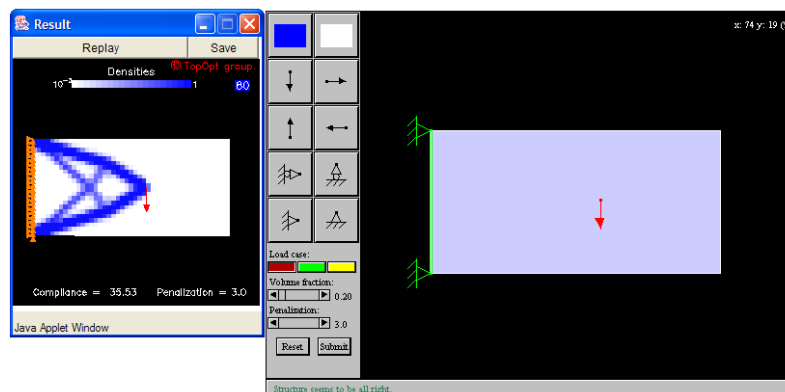
vibration of the wing and so forth. Each wing assembly had to pass a static load test and safety inspection before the assembly could be entered in the competition.

### Design variables:

Despite the constraints stated above the design space is relatively open. It can be characterized by looking at various design variables and configurations. The various lectures, interactions with faculty and staff and team interactions helped each team to focus or expand this list as appropriate: Aspect ratio, Wingspan, Wing chord; Angle of attack; Airfoil shape; Camber; Number of airfoil/sections; Number of support struts, Location of support struts; Winglet (end plate) geometry and attachment; Wing coating; and Wing/structure interface.

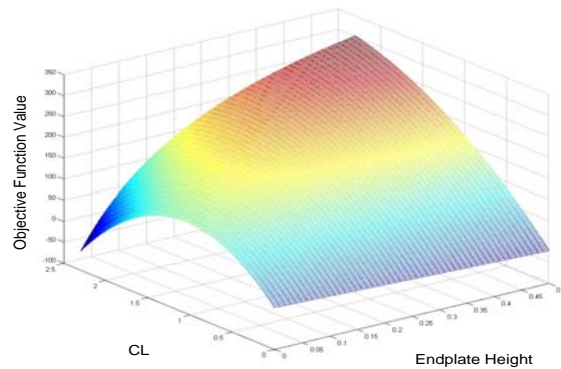
## DESIGN OPTIMIZATION

The students conducted a varied assortment of optimization routines. Some students made use of a structural topology optimization program, based on a pixel-like approach for their endplates. We utilized web-based optimization that was developed by Tcherniak and Sigmund [7], which can solve two-dimensional problems with rectangular design domains and a maximum number of 1000 design cells. The basic principle is that if a cell has a density of one, it means material should be used in the cell location. Compliance is used as the objective function, and the constraint is the volume fraction. This topology optimization is used to determine improved design layouts, but is only one of the considerations. Due to the aerodynamic effects that the endplate has on performance, there are other constraints and requirements on the endplate shape, and it is not possible to utilize this particular software for optimization given all of our performance metrics of interest. Figure 8 shows the graphical user interface (GUI) of the web-based optimization software and a sample optimization result.



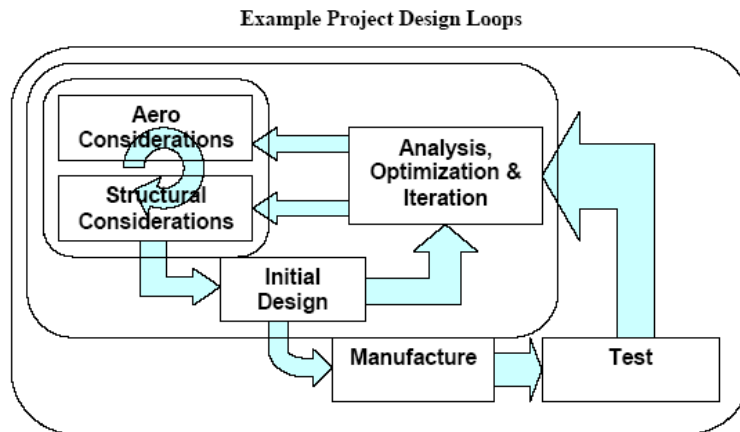
**Figure 8:** Web-based structural topology optimization (GUI and sample solution)

Some students were able to program (either using MATLAB or Microsoft Excel) a basic optimization routine using the objective function given above, see Eq. (1). The data entry from the FEA and CFD results was largely manual, but students were able to obtain basic trade-off curves for various design parameters. One of these response surfaces is illustrated in Figure 9, where one student team plotted their performance objective value as a function of endplate height and coefficient of lift. With endplate height being constrained, due to mass goals and structural requirements, the students were able to visualize where to direct their aerodynamic design efforts and goals.



**Figure 9:** Student Optimization: Performance Response Surface

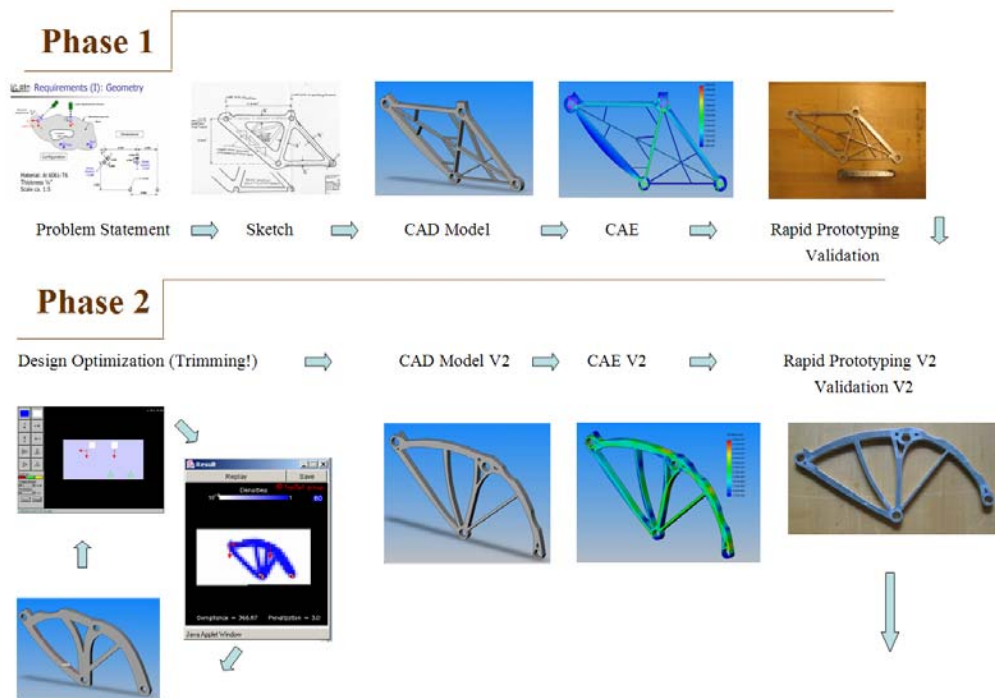
The overarching goals for optimization was to illustrate discipline versus system level optimization, and to give students a better appreciation of the trade offs involved in a complex, multi-disciplinary system. The example design loop given to students is shown in Figure 10. Students were advised to largely follow spiral design development model, and to continually iterate on their designs. *Iterations are considered undesirable in many traditional views and teachings of engineering design, because they are associated with rework and error correction. We do not subscribe to this view and explicitly teach the necessity of design iterations in the context of spiral development and continuous design improvement.*



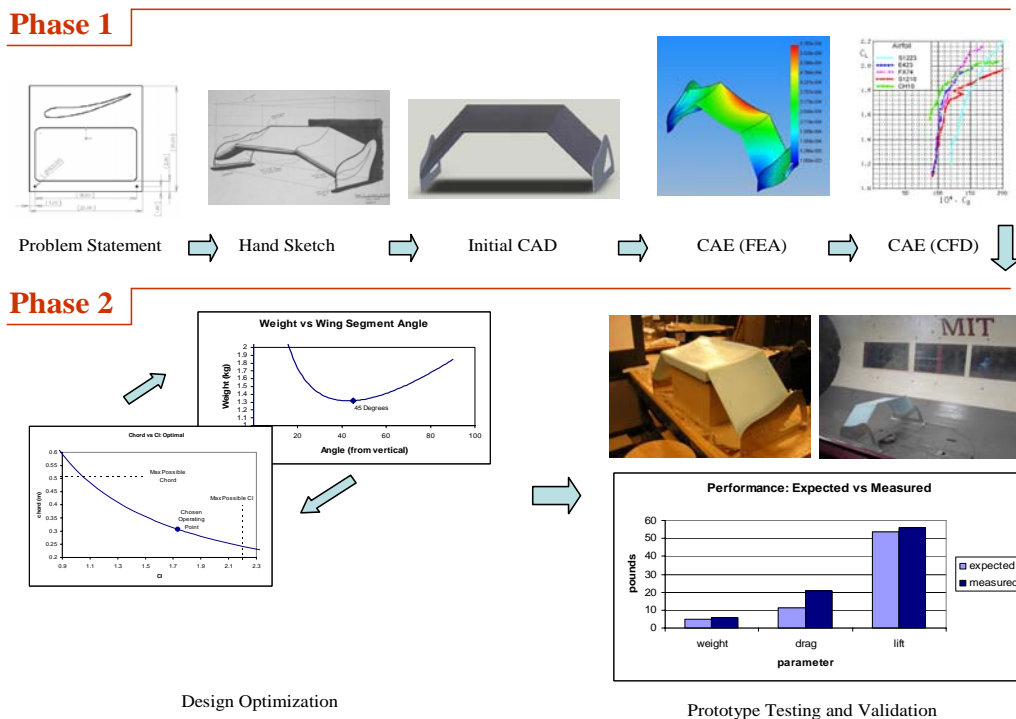
**Figure 10:** Design and Optimization Loops

## STUDENT DELIVERABLES

The entire set of deliverables for one of the student teams from each year's class are shown in Figure 11 and 12, respectively. The first is for Team 5, Racing Bike in 2004; and the second illustration is for Team 1, Trapezoidal Wing in 2005. These figures best illustrate how the student teams went through the design process and phases throughout the course, and how that compared to the theoretical work flow shown in Figure 1.



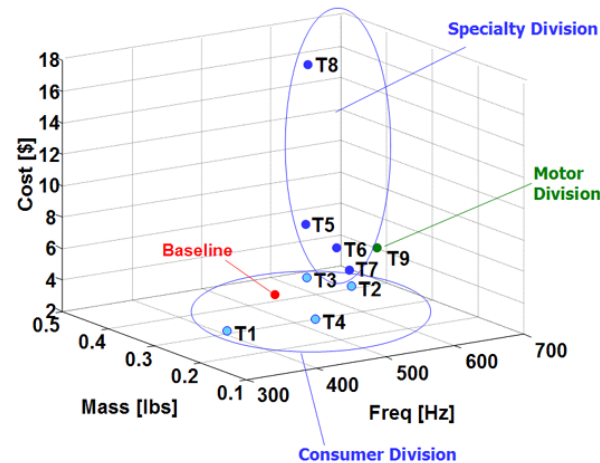
**Figure 11:** Example Student Work Flow from IAP 2004 (Team 5).



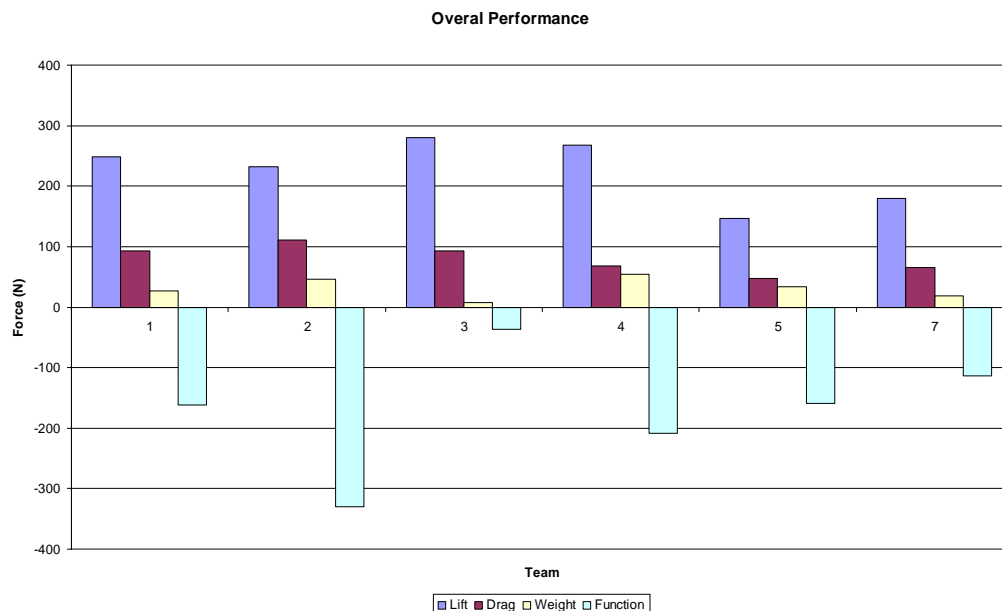
**Figure 12:** Example Student Work Flow from IAP 2005 (Team 1)

The functional performance of each student team's design from IAP 2004 is shown in Figure 13. It is important to note how students in the consumer division (T1-T4) made designs

that lie in the region where manufacturing cost is low, whereas specialty division (T5-T8) designs generally have better performance at the expense of manufacturing costs. The motor division (T9 team) had to deal with a forbidden zone as a constraint. For IAP 2005, the project changed slightly, and the teams were competing directly against each other. Given that this project was billed as a design competition, the efforts were to maximize the value of the performance function, Eq. (1). The results of the performances of the student teams are shown in Figure 14. It is also important to note that there were fewer teams in IAP 2005, and the objective was to maximize the performance function.



**Figure 13:** IAP 2004 Performance Results, T1-9 refer to student teams



**Figure 14:** IAP 2005 Performance Results, fourth bar shows objective function value

These results were presented at the final Critical Design Review and debated amongst the students and the guests present for each class's design review. This gave the students a deeper appreciation for the relationship between their design decisions and manufacturing

techniques and the resulting attributes of their product (that of mass, cost and deflection or downforce, drag, weight, and final objective performance). Also, students were able to have input in the required data corrections that were then applied to the results. The results between the teams were not much different when corrected for the test fixture drag and lift for the IAP 2005 project. However, due to test fixture displacement, the results of the FEA and test verification for the IAP 2004 project were significantly different.

At the end of this course, the students were able to articulate the merits of one design family over another, promote and defend the virtues of their own designs as well as debate the tradeoffs and necessary choices between design objectives. Also, students had a better realization of the balance between design variables and fixed parameters that affected their performance and had a better grasp of being able to identify those chief contributors to the performance.

## **COURSE EVALUATIONS**

In the last week of the course, an anonymous course evaluation was conducted. The survey consisted of a standard set of questions about the subject and instructor performance evaluation. A one-page reflective memo was also required for the students to write and submit. Thirteen students participated in the survey and reflective memo. A sample of results from the IAP 2005 survey follows:

(1) The subject stimulates my interest to learn more  
(1: strongly disagree — 3: neutral — 5: strongly agree) Score: 4.6

(2) The subject is relevant:  
(1: strongly disagree — 3: neutral — 5: strongly agree) Score: 4.7

(3) Overall quality of the subject:  
(1: poor — 3: good — 5: excellent) Score: 4.3

Some of the students' comments to the essay questions were:

(1) What are the best parts of the subject?  
"Actually getting to do some design work. The hours. The hands-on part was very nice."  
"I enjoyed pretty much the whole thing – getting to conceive, design, and build from scratch, something both exciting and practical (and challenging, too)."  
"Not being Course 16, I found all of it very interesting. I really took the class because I wanted to build. I really enjoyed the manufacturing, and surprisingly, I really had lots of fun with the xfoil program."

(2) What would improve the subject?  
"The learning curve was very steep for CAD. There should have been more help available."  
"Clarify grading a bit more. Make sure software is in working order beforehand."  
"...Should be worth more than 6, maybe 12, at least nine [units of credit]."

(3) Other Comments  
"Great course. I am now a more responsible engineer."

Other comments from the reflective memos offer more insight:

"This IAP we got to apply the skills I have learned in various other classes – structural, aerodynamic, and analytical tools – to do something that was both creative and applicable to the 'real world'. It really helped me see how useful my classes have been in understanding a practical engineering situation. ...16.810 taught me other important things for an engineer to consider, which might not be the easiest to learn in a pure classroom environment."

"The concept of the design spiral will stick with me... I am a firm believer in continuously improving any product that will have my name on it."

"It was interesting that we definitely learned this through the process of running into actual manufacturing problems...but I wouldn't complain about this part of the class. It's important to be able to work through problems that come up, because in the real world manufacturing won't be perfect either."

"I have a special appreciation for MDO because I first went about the design with the waterfall method instead of the spiral methodology that MDO follows... My inexperience and un-tuned instincts led me astray into thinking that maximizing the lift and then coming up with clever ways to reduce drag and would be a satisfactory strategy. ...starting again with the MDO mentality, I was reminded that drag scales with  $C_l$  squared and maximizing  $C_l$  would put our design on the low point of the curve in the design space."

"Comparing predicted results to the real results was the most intriguing part of the class because it forced the assumptions to be questioned."

"Although actual tests are costly, they are imperative to ensure that the design is working properly."

## CONCLUSIONS

This paper presented the second iteration of a new engineering design and rapid prototyping course for undergraduate students. The main learning objective of this course is for students to develop a holistic view of and initial competency in engineering design by applying a combination of human creativity and modern computational methods and tools to the synthesis of a structural component or simple subsystem. Lectures and hands-on activities are integrated for two phases of the course, the first being an initial run through a design and the second phase incorporating optimization and manufacturing. Activities include hand sketching, CAD design, Finite Element Analysis, CAM manufacturing, design optimization, and testing and validation. The class is nominally divided into small teams (2-3 students per team), and given the same requirements and performance objective. The resulting designs were varied and offered insight into not only the creative design process, but a good analysis and optimization of initial designs.

Overall responses from students were very positive for both IAP 2004 and IAP 2005. The majority felt that they benefited mainly from the fact that design activities were presented and executed as a coherent stream. Most students may not have experienced the design process in this way before, nor did most students have exposure to multi-disciplinary optimization or design spirals. Allowing the students to carry their design through iterations, rather than only once and looping the design (with or without formal optimization) was a crucial element of the pedagogy. This was particularly visible in IAP 2004, where students were able to design and manufacture products fully for both phases of the project. Although a concern of the previous years' students was addressed (that of a more challenging design project), the 2005 edition lacked multiple manufacturing and testing/validation loops due to the time constraint.



For most teams, the testing results did agree well with the Finite Element simulation and CFD results, however the data needed to be corrected for manufacturing errors and the test fixture (drag) effects. This was in sharp contrast to the IAP 2004 class, where the test fixture allowed the parts to move, and accurate test deflection data was not possible to obtain. Investigating likely error sources before actual testing will help improve the accuracy of the prediction, as well as expose students to the issues of testing before succumbing to its pitfalls. This is one area where the faculty and staff have to prepare prior to going through the test process with the students. Another area of concern that both years' students had was that they wanted more interactions between the student teams and earlier peer review to benefit from mutual experience, even if the course is cast as a design competition.

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### **Prof. Olivier de Weck**

Robert N. Noyce Assistant Professor of Aeronautics and Astronautics and Engineering Systems. Prof. de Weck has taught System Architecture (16.882/ESD.34J) and created a new Multidisciplinary System Design Optimization class (16.888/ESD.77) for graduate level students. His research interests are in Multidisciplinary Design Optimization and System Architecture. Before joining MIT he worked in a CAD/CAE/CAM intensive environment at McDonnell Douglas (now Boeing) on the F/A-18 aircraft program from 1991-1996.

### **Prof. Il Yong Kim**

Postdoctoral Associate in the MIT Department of Aeronautics and Astronautics from 2003-2004. Dr. Kim's expertise is in design optimization, and he has developed a computational tool that performs design optimization for structural topology optimization problems. He has taught CAD and advanced mathematics. He is a 2001 graduate of Korea Advanced Institute for Science and Technology (KAIST) and is currently a tenure track faculty member at Queen's University.

### **Christopher Graff**

Graduate research assistant in the Department of Aeronautics and Astronautics, Christopher Graff graduated from the Department in June of 2004, and took the first iteration of the course in IAP 2004. He has chosen to continue his studies at MIT and was the lead Teaching Assistant for IAP 2005. For his role in this course he was awarded the 2005 departmental teaching award.

**Bill Nadir**

Graduate research assistant in the Department of Aeronautics and Astronautics. He has CAD/CAE experience and has worked for several years as a spacecraft designer in industry (Boeing Satellite Systems). He served as Teaching Assistant for the course during IAP 2004.

**Aaron Bell**

An undergraduate student in the Dept. of Aeronautics and Astronautics, Aaron Bell took the first iteration of the course in IAP 2004 and was co-Teaching Assistant during IAP 2005.

**Peter Young, COL, USAF (ret.)**

Senior Lecturer in Aeronautics and Astronautics. Colonel Young (ret.) is a senior lecturer in the department of Aeronautics & Astronautics, specializing in developing and implementing 'hands on' undergraduate engineering projects. He has 29 years service on US Air Force space and missile programs. He is the director of CDIO initiatives in the Department of Aeronautics and Astronautics.

**Prof. Dave Wallace**

Associate Professor of Mechanical Engineering and Engineering Systems. Prof. Wallace is a tenured, associate professor in the Department of Mechanical Engineering. His research field is integrated computer aided design and industrial design and aesthetics. He teaches product design and industrial design in the department. He is the director of the MIT CADlab.

**Richard Perdichizzi, Dave Robertson, Todd Billings, Don Weiner, Paul Bauer, John Kane**

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