Engineering Systems Division (ESD)
Dept. of Aeronautics and Astronautics
Massachusetts Institute of Technology

February 2003
Rev. 4.0

Prof. O. de Weck, 33-406,deweck@mit.edu
Prof. K. Willcox, 37-471, kwillcox@mit.edu

Graduate Course Syllabus:

16.888/ESD.77J
Multidisciplinary System Design Optimization (MSDO)

Spring 2003

1. Course Description (*What does this course cover?)*

16.888/ESD.77J Multidisciplinary System Design Optimization (MSDO)
(Spring) H- Level
Units: 3-3-6
Prerequisites: 18.085 or permission of instructor
Lectures: MW 11-12:30 in 33-319
Labs: F 9-12 in 33-218
Grading: Letter, no final exam

Engineering systems modeling for design and optimization. Selection of design variables, objective functions and constraints. Overview of principles, methods and tools in multidisciplinary design optimization (MDO) for systems. Subsystem identification, development and interface design. Review of linear and non-linear constrained optimization formulations. Scalar versus vector optimization problems from systems engineering and architecting of complex systems. Heuristic search methods: Tabu search, simulated annealing, genetic algorithms. Sensitivity, tradeoff analysis and isoperformance. Multiobjective optimization and pareto optimality. System design for value. Specific applications from aerospace, mechanical, civil engineering and system architecture.
Instructors: O. de Weck, K. Willcox

Special Note:
This is the second time we are offering this course, this time under the permanent numbers 16.888 and ESD.77, respectively.

2. Purpose and Target Audience (*Who should take this course and why?)*

This course is offered for graduate students who are interested in the **multidisciplinary design aspects** of complex systems. These aspects appear frequently during the conceptual and preliminary design phases of complex new systems and products, where technical disciplines (structures, propulsion, aerodynamics, controls, optics etc…) and non-technical disciplines (lifecycle costing, environmental impact analysis, marketing, etc…) have to be tightly coupled in order to arrive at a competitive solution. During the product development process (PDP) both quantitative and qualitative effort streams are present, where qualitative work gives rise to quantitative questions and vice-versa. This course is **mainly focused on the quantitative aspects of design** and presents a unifying framework called "Multidisciplinary System Design Optimization" (MSDO). We will always attempt to show the strengths of MSDO, but also its limitations in the greater qualitative context of design. A simple way to say this is: "Qualitative, conceptual design and system architecting define the design vector, quantitative or computational design attempts to populate this vector with values that will lead to a good product or system".

The purpose of the course is to present tools and methodologies for performing system optimization in a multidisciplinary design context. Focus will be equally strong on all three aspects of the problem: (i) the **multidisciplinary** character of engineering systems, (ii) **design** of these complex systems, and (iii) tools for **optimization**. A more detailed discussion of these three aspects along with a working definition for "system" can be found in Appendix A. The course content will be applicable to the design of a broad range of systems including space systems, aircraft and transportation systems as well as the energy, civil architecture and telecommunications sectors, among others. This subject is designed to be **fundamentally different from a traditional university optimization course.**

Given the multidisciplinary nature of the course, we expect significant interest from ESD students, graduate students from the various School of Engineering departments and potentially a smaller group of Sloan students. The course is targeted for second year graduate and Ph.D. level students. This course would be suitable as a follow-on course to 16.882/ESD.34J System Architecture, without specifying it as a prerequisite. The expected enrollment for the MSDO course is:

Total enrollment: **24**[1] graduate students (Listeners only allowed if low enrollment)

Repartition:	30% (course 16 (AA))
	30% (ESD),
	20% (course 2 (ME) and course 1 (CEE))
	10% (course 15 (Sloan))
	10% (others)
	100% Total

3. Need Assessment (*Why has this course been added?)*

This course, we believe, will **add value to the current MIT offerings**. There is a strong and comprehensive program in optimization methods, mainly via course 15 (Sloan). However, to our knowledge, there appears to be no course that focuses on applying optimization techniques in a multidisciplinary design context. Important factors which are not covered by current courses include system characterization for multidisciplinary analysis and optimization, trade-off analysis, heuristic techniques and multiobjective optimization for the design of complex, multidisciplinary systems such as aircraft, spacecraft, transportation systems and communication networks.

[1] Capacity is limited to 30 students due to constraints of the "Design Studio", Room 33-218.

The current catalog of optimization courses at M.I.T. focuses heavily on two areas: The first is linear programming (simplex, interior points methods, large scale optimization) which are widely applicable and can solve many problems in management, revenue optimization, production planning and scheduling. The second area is related to systems, which can be described by a set of continuous PDE's. Here convex, constrained optimization methods such as steepest gradient search, projected gradient and Newton's method are important and covered well in the existing offerings. **In our view there appears to be a gap in the combined areas of multidisciplinary design, heuristic methods and multiobjective optimization**. Even though heuristic methods are mentioned in most optimization course syllabi, there is usually only one lecture (out of ~ 20) devoted to them. This does not reflect the true importance of these methods in MSDO. Multiobjective optimization is another emerging field, since many systems are usually trying to satisfy multiple, often conflicting performance, cost and risk objectives. The existence of this course will support teaching and research in system architecture and systems engineering, since many problems have non-linear objectives or constraints and are amenable to heuristic optimization and tradeoff analysis. As can be seen below the vast majority of optimization courses are taught in a management context and not in a systems design context. Also, courses in system architecture and product development are currently offered, however, they do not typically focus on quantitative methods and tools.

Some M.I.T. Courses, which are related to this offering, but are distinct from it:
2.739J Product Design and Development, S.D. Eppinger
15.093J Optimization Methods, D. Bertsimas, R. M. Freund
15.094 Systems Optimization: Models and Computation, D. Bertsimas, R. M. Freund
15.066J System Optimization and Analysis for Manufacturing, S.C. Graves, J.P. Clark
15.082 Network Optimization, T. L. Magnanti, A. S. Schulz
15.057 Systems Optimization, S. Schulz
16.410 Principles of Automated Reasoning and Decision-Making, B. Williams, E. Feron
16.882/ESD.34J System Architecture, E. Crawley, O. de Weck
16.910J Introduction to Numerical Simulation, J. K. White, J. Peraire, A. T. Patera
ESD.71J Engineering Systems Analysis for Design (formerly DSP), R. de Neufville

4. <u>Course and Learning Objectives</u> (*What will be achieved or learned?)*

The course will

- fill an existing gap in MIT's offerings in the area of analysis and optimization of multidisciplinary systems during the conceive and design phases
- develop and codify a prescriptive approach to multidisciplinary modeling and quantitative assessment of new or existing system/product architectures
- engage junior faculty and graduate students in the emerging research field of MSDO, while providing an opportunity to anchor the CDIO (conceive-design-implement-operate) principles in the graduate curriculum

The students will

- learn how MSDO can support the product development process of complex, multidisciplinary engineered systems
- learn how to rationalize and quantify a system architecture or product design problem by selecting appropriate objective functions, design parameters and constraints
- subdivide a complex system into smaller disciplinary models, manage their interfaces and reintegrate them into an overall system model
- be able to use traditional numerical optimization algorithms (e.g. sequential quadratic programming (SQP) and various modern heuristic optimization techniques such as simulated annealing (SA) or genetic algorithms (GA) and select the ones most suitable to the problem at hand
- perform a critical evaluation and interpretation of analysis and optimization results, including sensitivity analysis and exploration of performance, cost and risk tradeoffs
- be familiar with the basic concepts of multiobjective optimization, including the conditions for optimality and the computation of the Pareto front
- understand the concept of design for value and be familiar with ways to quantitatively assess the expected lifecycle cost of a new system or product
- sharpen their presentation skills, acquire critical reasoning with respect to the validity and fidelity of their MSDO models and experience the advantages and challenges of teamwork

5. <u>Pedagogy</u> (*How will these learning objectives be met?)*

Our goal is that the students will acquire knowledge and skills in the principles, methods (=techniques) and tools of multidisciplinary, computational design. To this end the course pedagogy will be using a number of instruments to achieve the learning objectives. Figure 1 shows the different pedagogical instruments used in the MSDO course as the sides of an imaginary folded box. In order to understand the box, one needs to look at it from all sides.

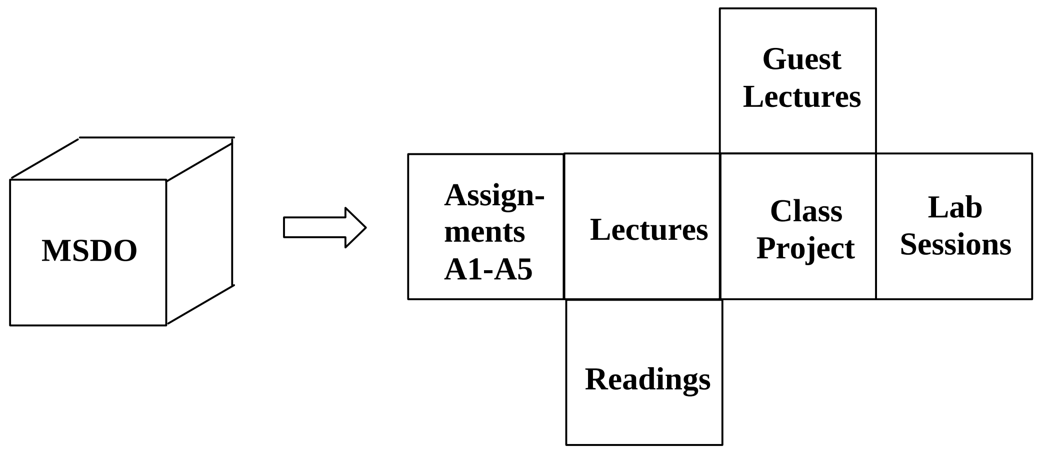

Fig. 1: Pedagogy of MSDO along with some specific examples

Lectures: The lectures are 90 minutes long and take place twice a week (usually MW). We lecture mainly using PowerPoint slides, but enhance the material with some active learning exercises. This is the main instrument for presenting the material. The lectures are broken down into four modules:

Module 1:	Problem Formulation and Setup	L1-L6
Module 2:	Optimization and Search Methods	L7-L13
--- Spring Break ---		
Module 3:	Multiobjective and Stochastic Challenges	L14-L20
Module 4:	Implementation Issues and Real World Applications	L20-L24

Guest Lectures: Will provide an outside perspective and show industrial applications
Readings: Will use the recommended textbooks and give an overview of the published literature in the field. Normally readings are assigned at the end of each lecture.
Laboratory Tutorials: Will introduce and exercise state-of-the art MDO tools in the lab.
Assignments: (Part a). Will challenge the students and ensure that all participants apply and deepen the theoretical knowledge from the lectures, regardless of their disciplinary background. (Part b) The second part of the assignments provides an opportunity to gradually develop the class project throughout the semester. This provides a coupling with the student's research interests.

Class Project: This is central to the success of the course. Students form small teams with between 1-3 members. They can choose between a number of sample projects provided by the faculty or pick a project based on their own research. The semester culminates with a final project presentation and writing a final report in the form of a conference or journal article. Students will form small groups of 1-3 according to their backgrounds and interests. Each group will select a multidisciplinary system to study throughout the semester. Examples include (but are not restricted to) an aircraft, a space system, an automobile, a communications network or a transportation system. A number of projects (airplane, communications satellites, space shuttle main tank, high speed business jet wing) are available as "canned" initial projects for those who do not have a research related system of their own. The faculty will screen the project proposals during the first two weeks and offer advice in problem selection and scoping if necessary. The projects will parallel the lecture content. The overall aim is to teach general tools and methods in the lectures, while allowing students to apply these tools to a specific application that is aligned with their background and interests.

6. Course Staff (*Who will teach and administer this course?)*

Instructors

Prof. Olivier de Weck (Goal Programming, Multiobjective Optimization, Space Systems)
Room 33-406, email: deweck@mit.edu, Phone: 253-0255

Prof. Karen Willcox (Aircraft MDO, Gradient Methods, Approximation, Design for Value)
Room 37-471, email: kwillcox@mit.edu, Phone: 253-3503

Course Assistant and Associate Lecturer

Dr. Il Yong Kim (Design Space Optimization, Structural Topology Optimization, MEMS)
Room 33-409, email: kiy@mit.edu

Guest Lecturers
See separate semester schedule

Contributors
A number of people are also contributing materials from their own research, including Cyrus Jilla (coupling, heuristic methods, multiobjective optimization), Dr. Lee Yang (integer programming), Dr. Il Yong Kim (design space optimization). These contributions will be acknowledged explicitly during the lectures.

7. <u>Detailed Syllabus</u> (*What are the detailed topics to be taught?)*

Module 1: Problem Formulation and Setup

a. System characterization:
   i. Identification of objectives, design variables, constraints, subsystems
   ii. System-level coupling and interactions
   iii. Examples of MSDO in practice
b. Subsystem model development:
   i. Model partitioning and decomposition, interface control
   ii. Subsystem model selection: fidelity versus expense
   iii. Model and simulation development and validation

Module 2: Optimization and Search Methods

c. Optimization and exploration techniques:
   i. Review of linear and nonlinear programming
   ii. Heuristic techniques: genetic algorithms simulated annealing, Tabu search, particle swarm optimization
   iii. Design Space Exploration: Design of Experiments (DOE): Full factorial search, parameter study, Taguchi/orthogonal arrays, Latin Hypercubes
   iv. Mixed integer programming (hub spoke / network problems)
d. Sensitivity and post-optimality analysis:
   i. Jacobian matrix, Hessian, finite differences
   ii. Adjoint methods and Lagrange multipliers
   iii.

Module 3: Multiobjective and Stochastic Challenges

e. Identification of competing factors and trades
   i. Goal programming, isoperformance and satisficing
   ii. Intuitive, experience-based design vs. systematic optimization
f. Multiobjective optimization:
   i. Weighted sum optimization, weak and strong dominance
   ii. Computation techniques for Pareto front
   iii. Utility theory of von Neumann and Morgenstern
   iv. Game theory and design optimization
g. Introduction to robust design
   i. Monte-Carlo Sampling, reliability analysis, Taguchi method

Module 4: Implementation Issues and Real World Applications

h. System assessment and extensions:
   i. What is optimality?
   ii. Design for value: including lifecycle costing
i. Implementation issues:
   i. Model reduction
   ii. Approximation techniques: response surfaces, kriging, neural networks
   iii. Visualization techniques in design optimization

8. Project Description (*What is the expected flow of the projects?)*

As described above, the small projects will form a fundamental part of the course. The projects will be executed in teams of 1-3 and be incorporated into the course via part (b) of the assignments, the final presentations and a final report[2]. Here we outline the expected progression of the project:

1. Select a multidisciplinary system to study.
2. Characterize the system, identifying important subsystem models and interactions, selecting important design variables, objective function and constraints.
3. Develop subsystem models. Existing tools may be used, or new models may be developed. Reexamine model partitioning and ensure interface control.
4. Benchmark against an existing system or design to measure the fidelity of the model.
5. Formulate the optimization problem. Select and apply an appropriate optimization technique after some initial sampling of the design space.
6. Identify competing trades in your system. Perform sensitivity analyses.
7. Obtain and evaluate systematic MSDO results for your system. Compare design choices with traditional, intuitive design processes. Identify limitations of subsystem models.
8. Identify additional objective functions. Perform multiobjective optimization.
9. Identify ways to expand your system and increase model fidelity. Review and critique your definition of "optimal".
10. Summarize the project and results in a short presentation at the end of the term and summarize you project in a paper.

9. Textbooks and Readings (*Do I need to buy a textbook?)*

Due to the fact that multidisciplinary system design optimization is a relatively young field, we know of no single textbook that would capture all the material of this course and be suitable as a classroom text. There are, however, a number of references that will be useful. Two of these have been ordered as "recommended" textbooks at the COOP. We don't have a mandatory textbook, but do recommend purchasing the following two:

Panos Y. Papalambros and Douglass J. Wilde, "Principles of Optimal Design – Modeling and Computation", 2nd edition, ISBN 0 521 62727 3, (paperback), Cambridge University Press, 2000

Garret N. Vanderplaats, "Numerical Optimization Techniques for Engineering Design", ISBN 0-944956-01-7, Third Edition, Vanderplaats Research & Development Inc., 2001

Two other books that will be on reserve in the Aeronautics & Astronautics library are:

R. E. Steuer." Multiple Criteria Optimization: Theory, Computation and Application". Wiley, New York, 1986.

David E. Goldberg, "Genetic Algorithms – in Search, Optimization & Machine Learning", Addison –Wesley, ISBN 0 201 15767-5, 1989

[2] The final report takes on the form of a conference or journal paper.

Other books and references are also available at the Aero-Astro library (33-111) or Barker, but might not be on reserve. Please contact Mrs. Eileen Dorschner (edorsch@mit.edu, 253-5666) for more information.

by Niels Olhoff (Editor), George I. N. Rozvany (Editor), "Structural and Multidisciplinary Optimization "

Natalia M. Alexandrov (Editor), M. Y. Hussaini (Editor)," Multidisciplinary Design Optimization : State of the Art" (Proceedings in Applied Mathematics Series ; No. 80)

Fogel, Owens and Walsh, "Artificial Intelligence Through Simulated Evolution", 1966

Roman B. Statnikov and Joseph B. Matusov. Multicriteria Optimization and Engineering. New York, Chapman and Hall, 1995.

Readings will be assigned at the end of each lecture. We will not check to see if student's have actually done the readings but we highly recommend them.

10. Physical and computational infrastructure (*What is the learning environment?)*

Lectures will be held in 33-319.

Labs will be held in 33-218 (**Design Studio**):

A course in multidisciplinary design optimization naturally has to have access to an environment that is conducive to concurrent engineering (CE) and computational work. We are fortunate to have such a facility, namely the **"Design Studio"** (Room 33-218) owned and operated by the Department of Aeronautics and Astronautics at MIT. This room was created as a consequence of the new strategic plan which calls for "lifecycle experiences" to be integrated into the curriculum. This course focuses on the **conceive** and **design** phases of CDIO, while attempting to take into account the downstream implementation and operation phases as much as possible. The Design Studio was carefully designed as a concurrent engineering facility; it is not just another computer cluster.

Since the Design Studio is heavily used, we ask that you **follow these rules**:
- You only have reserved access to the room during 16.888/ESD.77J lab hours, except…
- Off-class access is possible only if no other class is on-going, consult the schedule on the door of 33-218 before entering, be sensitive to others during peak times
- Full access requires your MIT electronic card and a username and password
- During off-class hours the workstations are used on a first-come-first-serve basis
- DO NOT LOCK UP a PC if you leave your seat for more than 5 minutes
- Don't leave any food, paper or personal items laying around
- Clean up when you are done, this is a professional environment
- Make sure that all the equipment is working, the printer is stocked, unjammed etc…
- Report any system failures, network problems etc… immediately to the system administrator

The system administrator for the Design Studio (33-218) is:

Frederick ("Fred") J Donovan
Email: fjd@mit.edu
Phone: (617) 253-3389
Address: 33-332
Department: Aero & Astro
Title: Systems Manager, Aeronautics & Astronautics

The Design Studio is equipped with 14 PC computers that are networked together on the **AA-Design** local area network (LAN). Additional computers are located in the breakout rooms. The class folder is located on the local intranet at: \\aero-astro\\16.888

For their projects, the students will be free to choose the platform and software of their choice. They can code their simulation modules in Matlab, Excel (Visual Basic), Java, Fortran or C/C++. In terms of using specific software for MSDO, two generous software contribution have been made to us for this course:

iSIGHT: This is currently the most popular multidisciplinary design optimization software available on the market. This tool is state-of-the-art and is used in many large corporations that focus on the design and development of large, complex engineering systems. Each PC in the Design Studio will be able to run iSIGHT from the central license server. The program can be "wrapped around" any user specific simulation code (e.g. in Excel, Matlab, C, FORTRAN…) and has excellent design space exploration, optimization and robust design capabilities. An introduction to this tool will be provided in class. The developer of iSIGHT is Engineous Software, Inc., located in North Carolina (http://www.engineous.com). The origin of this tool is the "Software Robot" developed by Dr. Siu Tong during his doctoral research at MIT, Department of Aeronautics and Astronautics, from 1979-1983. We thank Dr. Tong, who is the Co-founder and Chairman of the Board of Engineous Software Inc. for his support.

Based on last year's experiences Engineous Inc. has agreed to start offering a student version of iSIGHT. Before releasing this version on the open market, we , together with Georgia Tech, have agreed to lead the BETA testing effort.

iSIGHT academic BETA program: As a participant in this class you are eligible to receive a free CD-ROM with the iSIGHT academic BETA software. You can install this software on your personal laptop, laboratory PC or home computer without restrictions. We encourage that you try using this software for the class project. This version has the full professional functionality of iSIGHT, except for being limited to 8 design variables. In return we will collect some demographic data and you will be expected to provide periodic feedback during the term by filling in a questionnaire. The license runs out on June 30, 2003. The CD-ROMS will be handed out during the second or third week of the semester, after the class roster has stabilized.

CO: This software tool is distributed by Oculus Technologies Corp. (http://www.oculustech.com/), headquartered here in Boston. Oculus' software, CO™, provides the "glue" to tie disparate applications, platforms, and organizations together. It creates dynamic data links that bring information from the source to your desktop. CO™ is suitable for the PC-networked environment of our Design Studio 33-218. It enables real-time iterations and trade-off analyses, while improving decision making across different disciplines. The underlying technology for CO was conceived within MIT's CADLab under the direction of Prof. David Wallace, to meet the needs of product design, development and manufacturing industries. The original research sponsorship occurred via the Center for Innovative Product Development (CIPD) and the National Science Foundation. CO is based on the DOME (Distributed Object-based Modeling Environment) protocol. Many thanks to Ted Pawela, Jason Vanden Akker and Chris Williams of Oculus for their support.

The students can use this software free of charge for the duration of the course. During the first class you will be required to sign a standard software user agreement.

We ask you not to contact Engineous and Oculus directly, but to funnel all problems and request via the faculty and the TA.

The use of commercial disciplinary codes such as MSC/Nastran for structural modeling, ProEngineer, SolidWorks for Computer Aided Design or CPLEX for the solution of linear programs is also a possibility for your projects. We are attempting to install the FEMLAB toolbox for MATLAB-based finite element analysis as well. There will be less emphasis on this point, however, since proficiency in these tools takes a long time to acquire and many of these codes have steep learning curves. Hence, the emphasis of the course is rather on learning the process of setting up, solving and interpreting multidisciplinary problems, rather than on creating physical models of very high fidelity as would be expected in an industry environment.

Finally, it is a long-term vision of the instructors to not only be a user of the Design Studio (33-218), but also to contribute to furthering its physical and intellectual infrastructure. We hope to achieve this by implementing various multidisciplinary design processes and approaches, gaining experience with multidisciplinary software tools, and improving the course and facility from year-to-year based on your suggestions, criticism and project experiences.

The course will be administered on-line with the STELLAR system. Our locker can be found at:

http://stellar.mit.edu/dept/course16.html

Please register for an account online. Paper handouts will be provided during the first two weeks of the course. After that students are expected to download and/or print out the lectures and assignments on their own.

11. Grading (*How will the learning success be measured?)*

There will be two types of assignments in the course:

"Assignments A1-A5" (5 Total):
Part (a): Small, simple problems to be solved individually, many just by hand or with a calculator. Goal is to ensure learning of the key ideas regardless of chosen project
Part (b): Application of theory to a project of your choice from either existing class projects or a project related to your research. Solution individually or in teams of two. Teams of three are possible with permission of the faculty.

The assignments are due biweekly. Typically an assignment is handed out on a Monday, a related tutorial is given on the following Friday and the assignment itself is due on a Monday two weeks later.

"Class Project":
The class project is our main means of assessing whether you can learn the material at a deeper level and apply it to a graduate level research project. There are two major deliverables here towards the end of the term:

i) Project Presentation (ca. 30 minutes including Q&A)
ii) Final Report in the format of a Journal or Conference article

The grading will be on the letter scale A-F and be weighted as follows:

Assignments A1-A5	50%	(10% each assignment)
Project Presentation	20%	
Final Project Report	20%	
Active Participation/Attendance	10%	
Total	100 %	

No mid-term or final exams.

Appendix A

This appendix discusses the fundamental aspects of the MSDO course:

Multidisciplinary

A key component of this course is learning how to integrate different models from various disciplinary fields together into a single macro-model. All too often specialists in different fields (structures, fluids, propulsion, controls etc.) exert a great deal of effort modeling and designing within their area of expertise with little understanding of how their design decisions affect other subsystems within the entire macro-system. Also frequently lacking is an understanding of how such design decisions impact system lifecycle cost and program risk. Understanding of and fluency in integrated, multidisciplinary modeling is essential to the success of contemporary and future complex systems.

System

A system is a physical or virtual object that is composed of more than one element and that exhibits some behavior or performs some function as a consequence of interactions between these constituent elements.

Design

This course focuses on engineering design problems (e.g. aerospace vehicles, transportation systems, communication networks) and not primarily management problems (resource allocation, supply chain optimization, revenue management, etc.). As such, students should have a background and interest in engineering and system or product design and have had previous exposure to optimization. The course will be a good complement to existing courses in product development and system architecture, which do not typically present a multitude of quantitative methods and tools.

Optimization

Optimization is a mathematical method and gives rise to a number of algorithmic tools. As such it represents a bridge, which enables the use of integrated multidisciplinary models to do more effective design engineering work. It should be stressed that the use of optimization is *not* intended to remove the human from the design loop. Rather, optimization enables engineers and system architects to explore vast design spaces, often resulting in non-intuitive insights. This may result in system designs that are more cost-effective compared to previously considered traditional designs.