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Multidisciplinary System Design Optimization (MSDO)

Introduction

Lecture 1

4 February 2004

Prof. Olivier de Weck
Prof. Karen Willcox

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Introductions

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Today's Topics

- Course Rationale
- Role of MSDO in Engineering Systems
- Learning Objectives
- Pedagogy and Course Administration
- A historical perspective on MDO
- MSDO Framework introduction
- The "dairy farm" sample problem

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Course Rationale

- Computational Design and Concurrent Engineering (CE) are becoming an increasingly important part of the Product Development Process (PDP) in Industry

- MIT offerings strong in linear programming and constrained convex optimization (single objective)

- However, there is a perceived gap at MIT:
  - mostly management, not design focus
  - multiobjective optimization
  - MDO vibrant research field but no course to represent it

- This is NOT a traditional optimization course: M-S-D-O

Role of MSDO in Engineering Systems

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Goal: Create advanced and complex engineering systems that must be competitive not only in terms of performance, but also in terms of manufacturability, serviceability and overall life-cycle cost effectiveness.

Need: A rigorous, quantitative multidisciplinary design methodology that can work hand-in-hand with the intuitive non-quantitative and creative side of the design process.

⇨ This class presents the current state-of-the-art in concurrent, multidisciplinary design optimization (MDO)

Product Development Process

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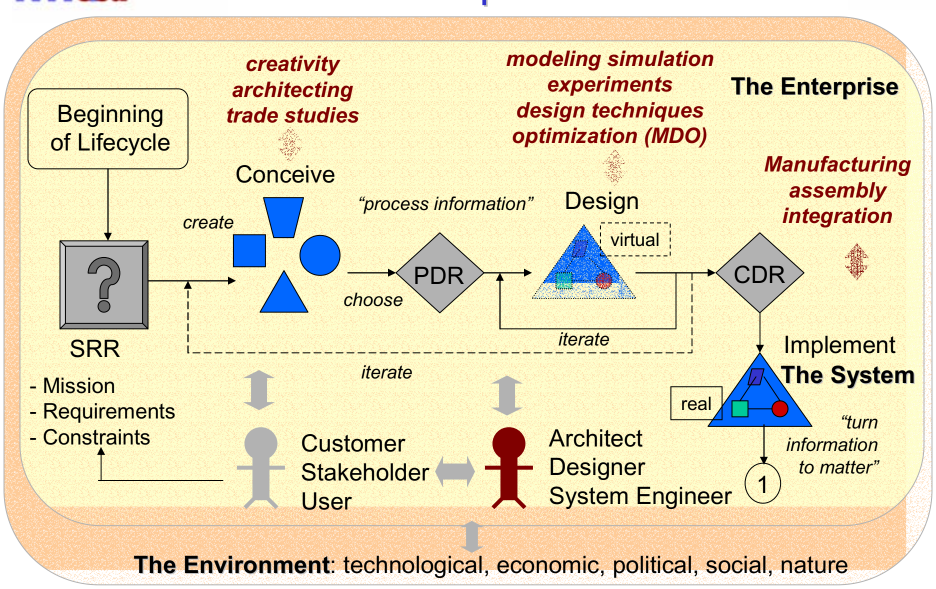

Nexus Spacecraft Example

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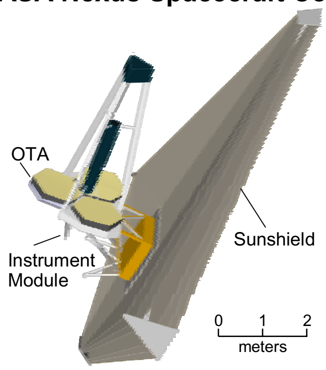
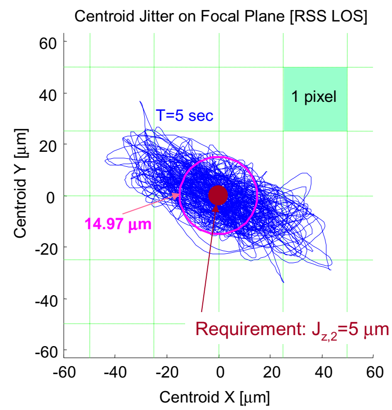
NASA Nexus Spacecraft Concept





<u>Goal:</u> Find a "balanced" system design, where the flexible structure, the optics and the control systems work together to achieve a desired pointing performance, given various constraints

Automotive Example

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Ferrari 360 Spider

Goal: High end vehicle shape optimization while improving car safety for fixed performance level and given geometric constraints

Reference: G. Lombardi, A. Vicere, H. Paap, G. Manacorda, "Optimized Aerodynamic Design for High Performance Cars", AIAA-98-4789, MAO Conference, St. Louis, 1998

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Course Objectives

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The course will

- fill an existing gap in MIT's offerings in the area of simulation 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 designs
- engage junior faculty and graduate students in the emerging research field of MDO, while anchoring the CDIO principles in the graduate curriculum

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Learning Objectives (I)

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The students will

(1) learn how MSDO can support the product development process of complex, multidisciplinary engineered systems

(2) learn how to rationalize and quantify a system architecture or product design problem by selecting appropriate objective functions, design variables, parameters and constraints

(3) subdivide a complex system into smaller disciplinary models, manage their interfaces and reintegrate them into an overall system model

Learning Objectives (II)

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(4) be able to use various optimization techniques such as sequential quadratic programming, simulated annealing or genetic algorithms and select the ones most suitable to the problem at hand

(5) perform a critical evaluation and interpretation of simulation and optimization results, including sensitivity analysis and exploration of performance, cost and risk tradeoffs

(6) be familiar with the basic concepts of multiobjective optimization, including the conditions for optimality and the computation of the pareto front

Learning Objectives (III)

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(7) 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

(8) 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

⇨ How to achieve these learning objectives ?

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MSDO Pedagogy

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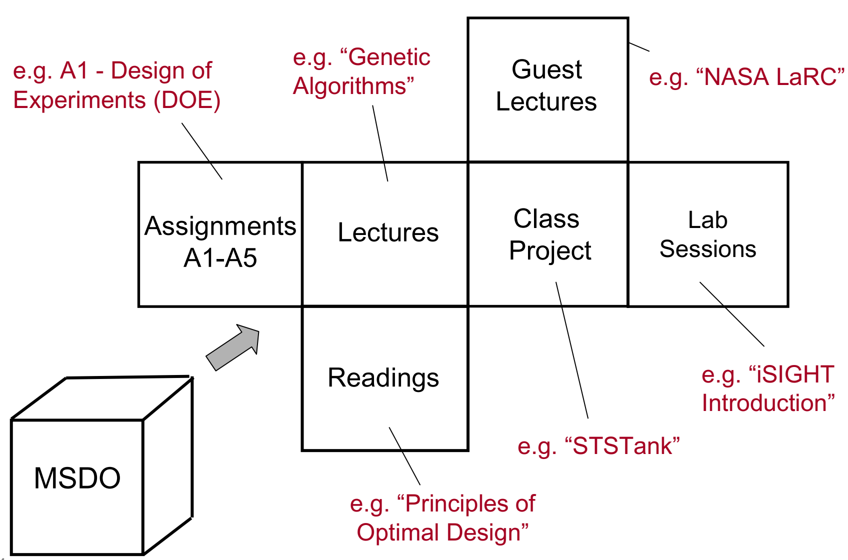

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Assignments

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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 or three.

- Assignments A1-A5 scheduled bi-weekly.
- Usually handed out Monday, Tutorial on Friday, due on a Monday two weeks later

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Lectures

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Lecture schedule in separate document.

Module 1: Problem Formulation and Setup

Module 2: Optimization and Search Methods

--- Spring Break ---

Module 3: Multiobjective and Stochastic Challenges

Module 4: Implementation Issues and Applications

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Class Project

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Option A – Use a pre-existing project

These are prepared simulation codes that you can use as your class project for solving part (b) of the assignments in lieu of a personal research-related problem:

\\AERO-ASTRO\16.888\AIRCRAFT (C-Code)
\\AERO-ASTRO\16.888\COMSATS (MATLAB)
\\AERO-ASTRO\16.888\SHUTTLETANK (Excel)
\\AERO-ASTRO\16.888\SUPERSONIC (Excel)

Option B – Formulate your own project

-This is an opportunity to push your research forward

-Form teams of 1-3 students

-Must be a design problem, must be multidisciplinary

-Write 1 page project proposal in A1

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Lab Sessions

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This room is the "Design Studio" …. **NOT** just another computer cluster. There is a lot of thought behind the façade.

"Complex Systems Development and Operations Laboratory"

Result of the most recent strategic plan of the Dept. of Aeronautics and Astronautics at MIT. New Focus:

- CDIO
- System Architecture and Systems Engineering
- Aerospace Information Engineering

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Tools and Infrastructure

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- **Physical Infrastructure: Design Studio 33-218**
- **Computational Infrastructure:**
  - Class folder: \\AERO-ASTRO\16.888
  - **Located on AA-DESIGN PC network**
  - Will setup individual usernames and passwords

- **Software Infrastructure:**
  - Matlab, Excel, C-compiler
  - iSIGHT - donated by Engineous Software Inc.
  (Participate in iSIGHT academic BETA test program)
  - CO - donated by Oculus Technologies Corp.

Readings

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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 - Recommended

Garret N. Vanderplaats, "Numerical Optimization Techniques for Engineering Design", ISBN 0-944956-01-7, Third Edition, Vanderplaats Research & Development Inc., 2001- Recommended (out of print?)

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

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

⇨ will assign at the end of each lecture

Guest Lectures

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Guest Lecture 1:

3 Mar **Dr. Jaroslaw Sobieski, NASA LaRC**
Overview of MDO, Video Lecture

Guest Lecture 2:

14 Apr **Dr. Peter Fenyes, General Motors Research Center**
IFAD/CDQM – MDO in vehicle development

During the semester:

- **Dr. Cyrus Jilla: Simulated Annealing**
- **Dr. Rania Hassan: Particle Swarm Optimization**
- **Dr. Il Yong Kim: Design Space Optimization**
- **Prof. Dan Frey : Robust Design**

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Grading

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Assignments A1-A5*	50%
Project Presentation	20%
Final Report (Paper)	20%
Active Participation	10%
	100 %

No mid-term or final exams

**** Each Assignment counts 10%***

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Introduction to stellar.mit.edu

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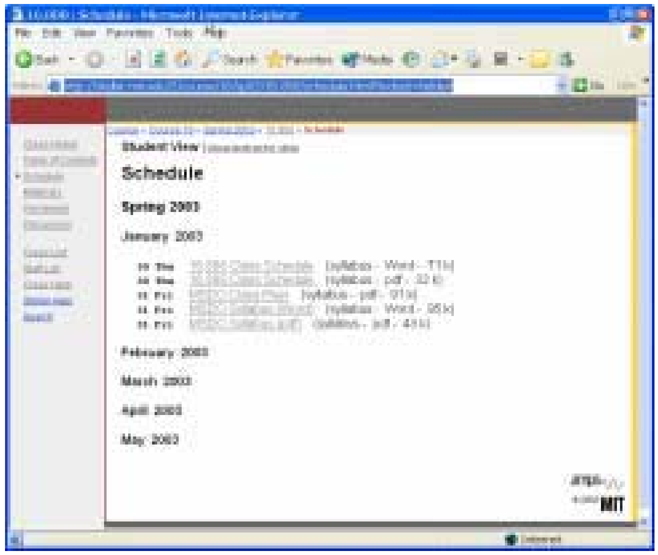

Register in stellar system by 2/6/2004

Historical Perspective on MDO

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The need for MDO can be better understood by considering the historical context of progress in aerospace vehicle design.

- **1903** Wright Flyer makes the first manned and powered flight.
- **1927** Charles Lindbergh crosses the Atlantic solo and nonstop
- **1935 DC-3** enters service (12,000 to be produced)
- **1958 B707** enters service
- **1970 B747** enters service
- **1974 A300** enters service
- **1976** Concorde enters service

Growth in design requirements

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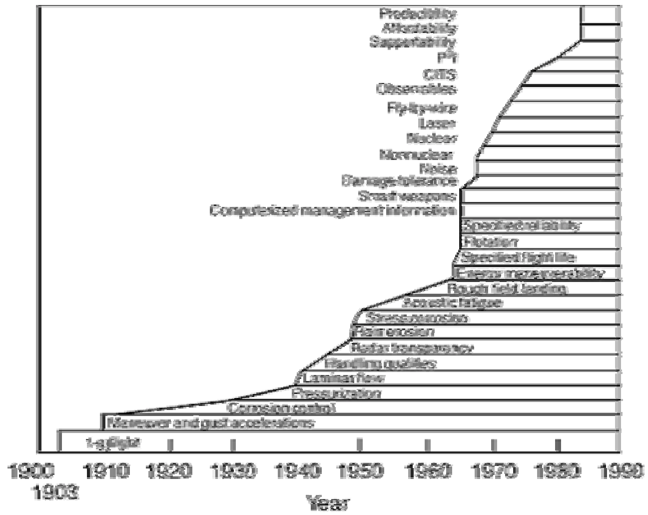

Design requirements growth for aerospace vehicles.

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1970-1990 Cold War and Maturity

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- Big slump in world economy ("oil crisis" 1973), airline industry and end of Apollo program leads to a reduction of engineering workforce around 25%
- Two major new developments: Computer aided design (CAD), Procurement policy changes for airlines and the military
- Earlier quest for maximum performance has been superseded by need for a "balance" among performance, life-cycle cost, reliability, maintainability and other "-ilities"
- Reflected by growth in design requirements, see next slide. Competition in airline industry drives operational efficiency.

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1990-present

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- Multidisciplinary design extended to other industries: spacecraft, automobiles, electronics and computers, transportation and energy/power suppliers
- Thrusts in government and industry to improve productivity and quality in products and processes
- Design process: Globalization results in distributed, decentralized design teams, high performance PC has replaced centralized super-computers, disciplinary design software (Nastran, CAD/CAM) very mature, Internet and LAN's allow easy information transfer
- Advances in optimization algorithms: e.g. Genetic Algorithms, Simulated Annealing, MDO software, e.g. iSIGHT

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Design Freedom versus Knowledge

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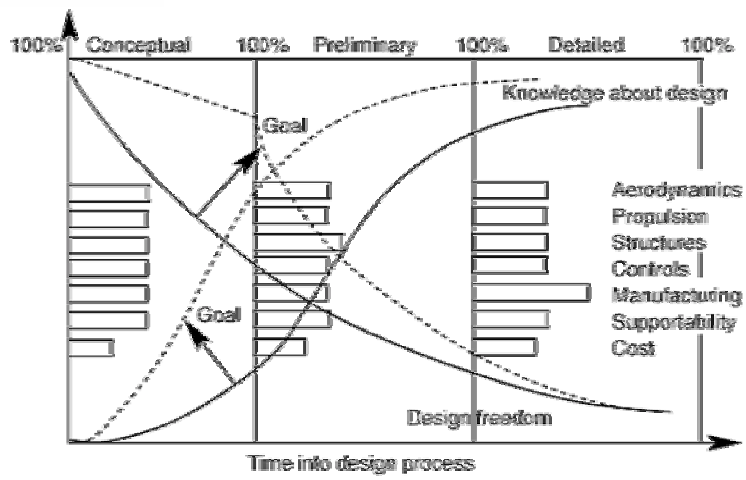

Goal of MDO: Gain design knowledge earlier and retain design freedom longer into the development process.

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Key motivation: Control of Lifecycle costs

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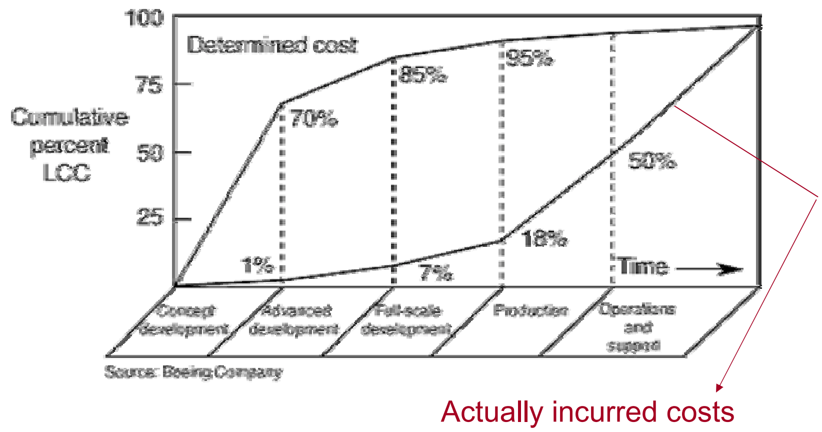
Life cycle-cost committed versus incurred by life-cycle phase
(Ballistic missile system)



Leverage in the development process.

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Definitions

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Multidisciplinary - comprised of more than one traditional disciplinary area described by governing equations from various physical, economic, social fields

System - A system is a physical or virtual object that exhibits some behavior or performs some function as a consequence of interactions between the constituent elements

Design - The process of conceiving and planning an object or process with a specific goal in mind. In the context of this class this refers to the conceiving of a system that will subsequently be implemented and operated for some beneficial purpose.

Optimization - To find a system design that will minimize some objective function. The objective function can be a vector comprising measures of system behavior ("performance"), resource utilization ("time, money, fuel ...") or risk ("stability margins…").

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Problem Formulation and Setup

(NLP)

$$\min \mathbf{J}(\mathbf{x},\mathbf{p}) \longrightarrow \textbf{objective}$$

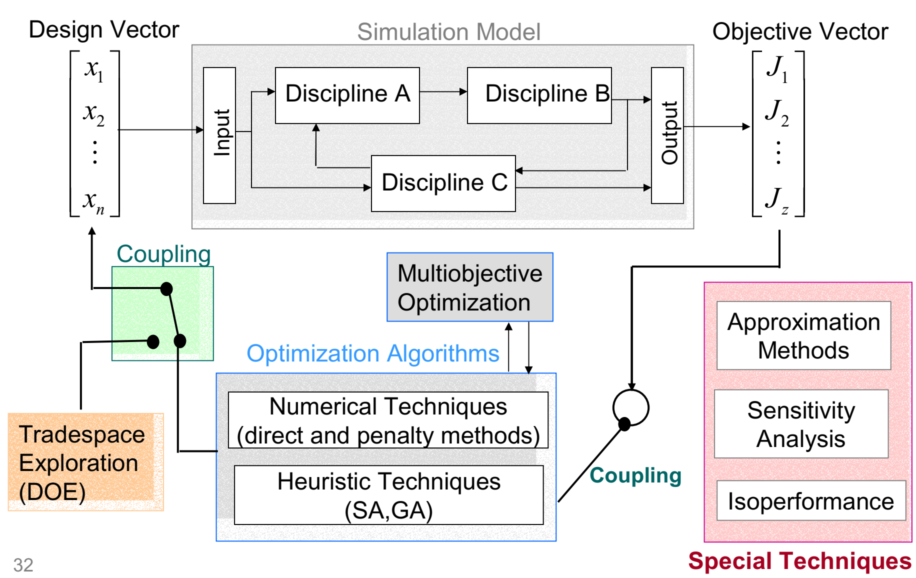
$$\text{s.t.} \quad \mathbf{g}(\mathbf{x},\mathbf{p}) \le 0, \quad \mathbf{h}(\mathbf{x},\mathbf{p}) = 0 \longrightarrow \textbf{constraints}$$

$$x_{i,LB} \le x_i \le x_{i,UB} \longrightarrow \textbf{bounds}$$

$$\text{where} \quad \mathbf{J} = \begin{bmatrix} J_1(\mathbf{x}) & \cdots & J_z(\mathbf{x}) \end{bmatrix}^T$$

$$\mathbf{x} = \begin{bmatrix} x_1 & \cdots & x_i & \cdots & x_n \end{bmatrix}^T \longrightarrow \textbf{design vector}$$

MSDO Framework



Challenges of MSDO

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- Deal with design models of realistic size and fidelity that will not lead to erroneous conclusions
- Reduce the tedium of coupling variables and results from disciplinary models, such that engineers don't spend 50-80% of their time doing data transfer
- Allow for creativity, intuition and "beauty", while leveraging rigorous, quantitative tools in the design process. Hand-shaking: qualitative vs. quantitative
- Data visualization in multiple dimensions
- Incorporation of higher-level upstream and downstream system architecture aspects in early design: staged deployment, safety and security, environmental sustainability, platform design etc...

Simple example (I)

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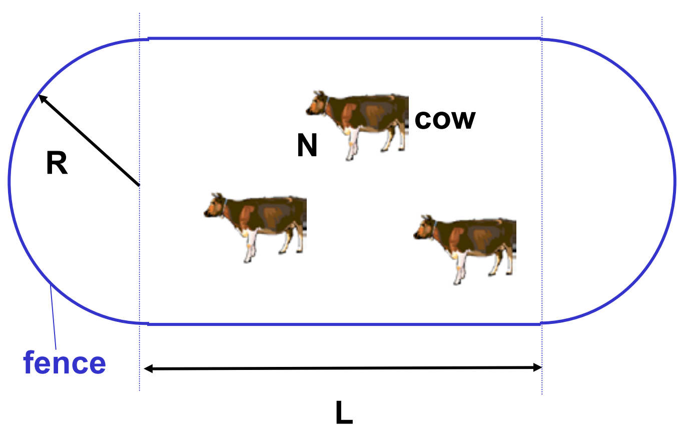
"Dairy Farm" sample problem

L - Length
N - # of cows
R - Radius



Goal: maximize Profit P

Simple example (II)

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Agricultural Model: **Units**

Area:	$A = 2LR + \pi R^2$	**[m^2]**
Fence Perimeter:	$F = 2L + 2\pi R$	**[m]**
Milk Production per Cow:	$M = 100 \cdot \sqrt{A/N}$	**[liters]**

Economic Model:

Cost:	$C = f \cdot F + n \cdot N$	**[$]**
Income:	$I = N \cdot M \cdot m$	**[$]**
Profit:	$P = I - C$	**[$]**

Parameters: f=100$/m n=2000$/cow m=2$/liter
Constraint: C<= 100,000 $

⇨ **Get same results analytically ?**

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Summary

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- **Learning Objectives:**
  - **- decompose and integrate multidisciplinary design models**
  - **- formulate meaningful problems mathematically**
  - **- explore design space and understand optimization**
  - **- critically analyze results, incl. sensitivity analysis**
- **Understand current state of the Art in MSDO**
  - **- see depth and breadth of applications in industry & science**
  - **- get a feel for interaction of quantitative-qualitative design**
  - **- understand limitations of techniques**
  - **- good overview of literature in the field**
- **Benefit your research directly … and have fun !**

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Reading Assignment

- **Read Course syllabus carefully by 2/6/2004**

- **Read Chapter 1**
  - **Papalambros, "Principles of Optimal Design"**
  - **Before: Monday – February 9, 2003**

- **Read 1991 MDO White Paper**
  - **http://endo.sandia.gov/AIAA_MDOTC/sponsored/aiaa_paper.html**
  - **Before: Monday – February 9, 2003**