16.842 Fundamentals of Systems Engineering

Lecture 6 – Design Definition and Multidisciplinary Design Optimization

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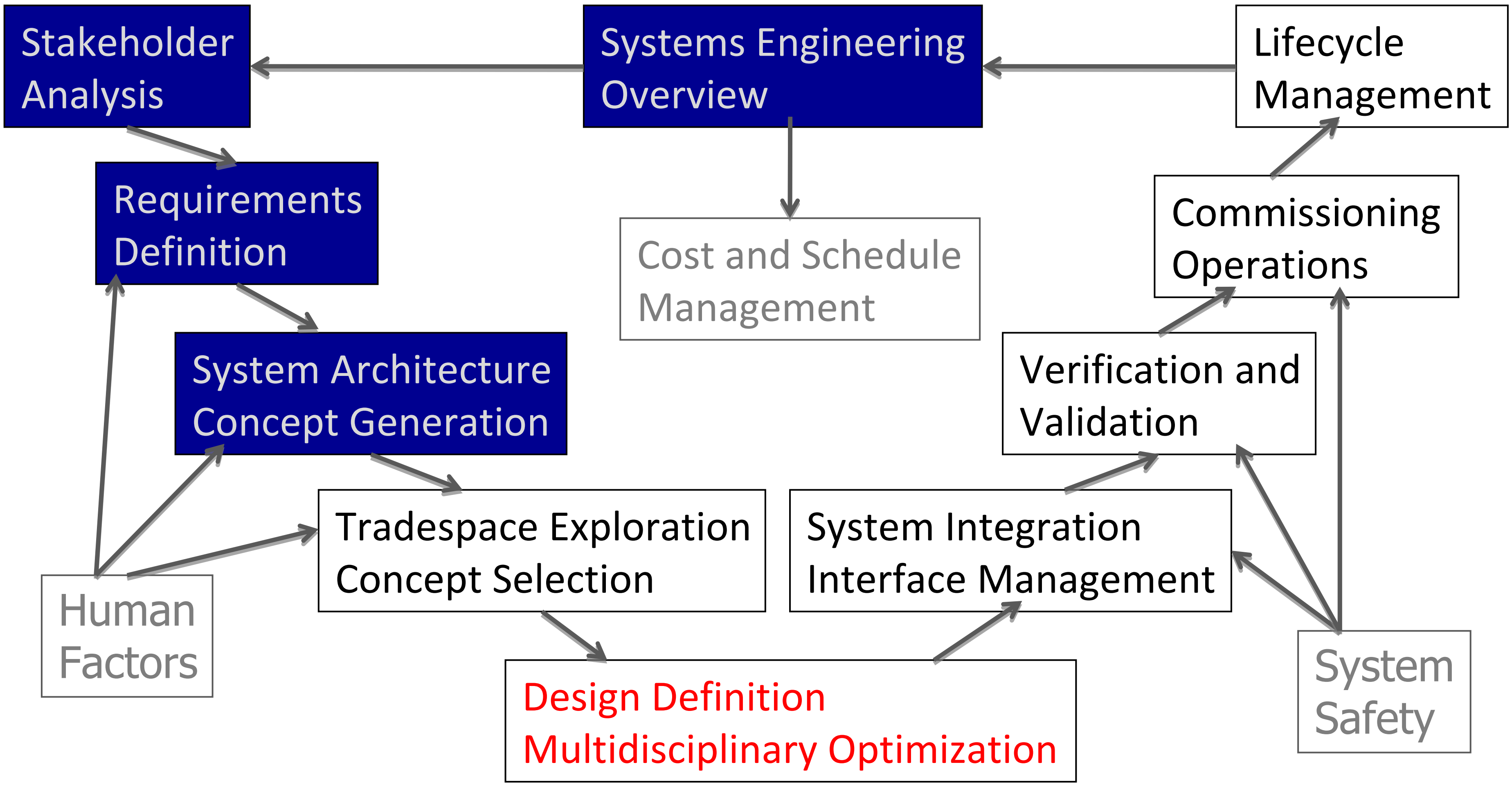
V-Model – Oct 16, 2009



Outline

- NASA Design Definition Process
  - Process Overview
  - Slides from Lecture 5b on Stellar
- Multidisciplinary Design Optimization
  - What it is and where it fits in…
  - Motivation
  - Roots
  - Method
  - Limitations
  - Future Trends

Design Solution Definition Process

- The Design Solution Definition Process is used to translate the outputs of the Logical Decomposition Process into a design solution definition

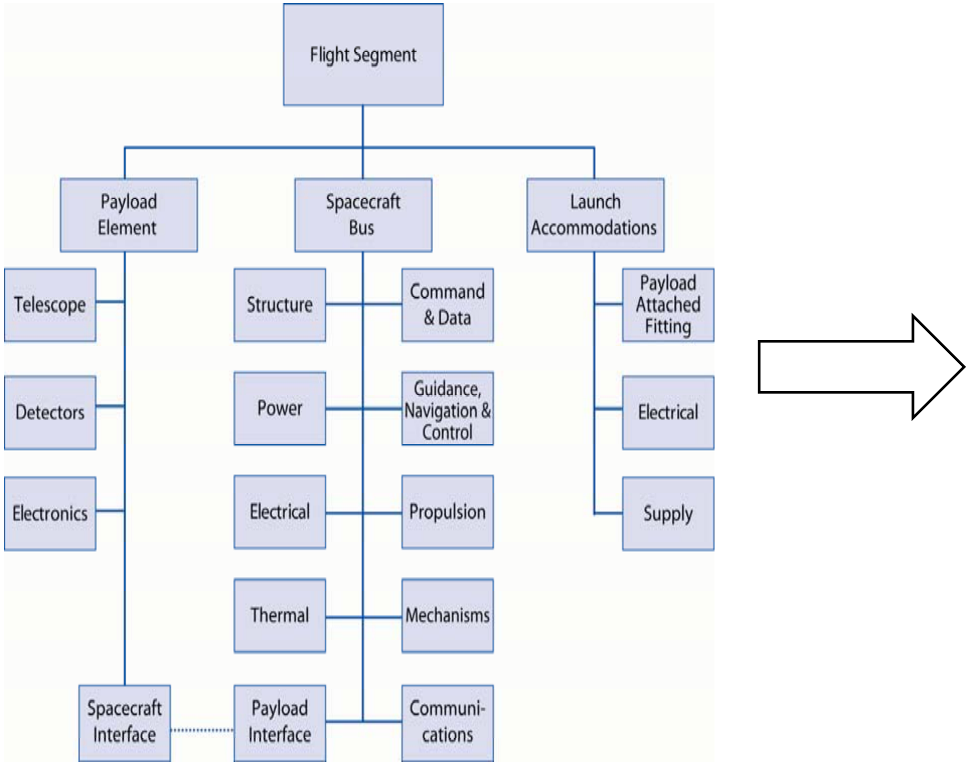


Figure 4.3-2 Example of a PBS

Design Solution Definition: the specification of a rocket, for example

Design Solution Importance

- Define solution space
- Develop design alternatives
- Trade studies to analyze
  - Alternate Design
  - Cost, performance, schedule
- Select Design Solution
- Drive down to lower level
- Identify enabling products

Design with the end in mind!

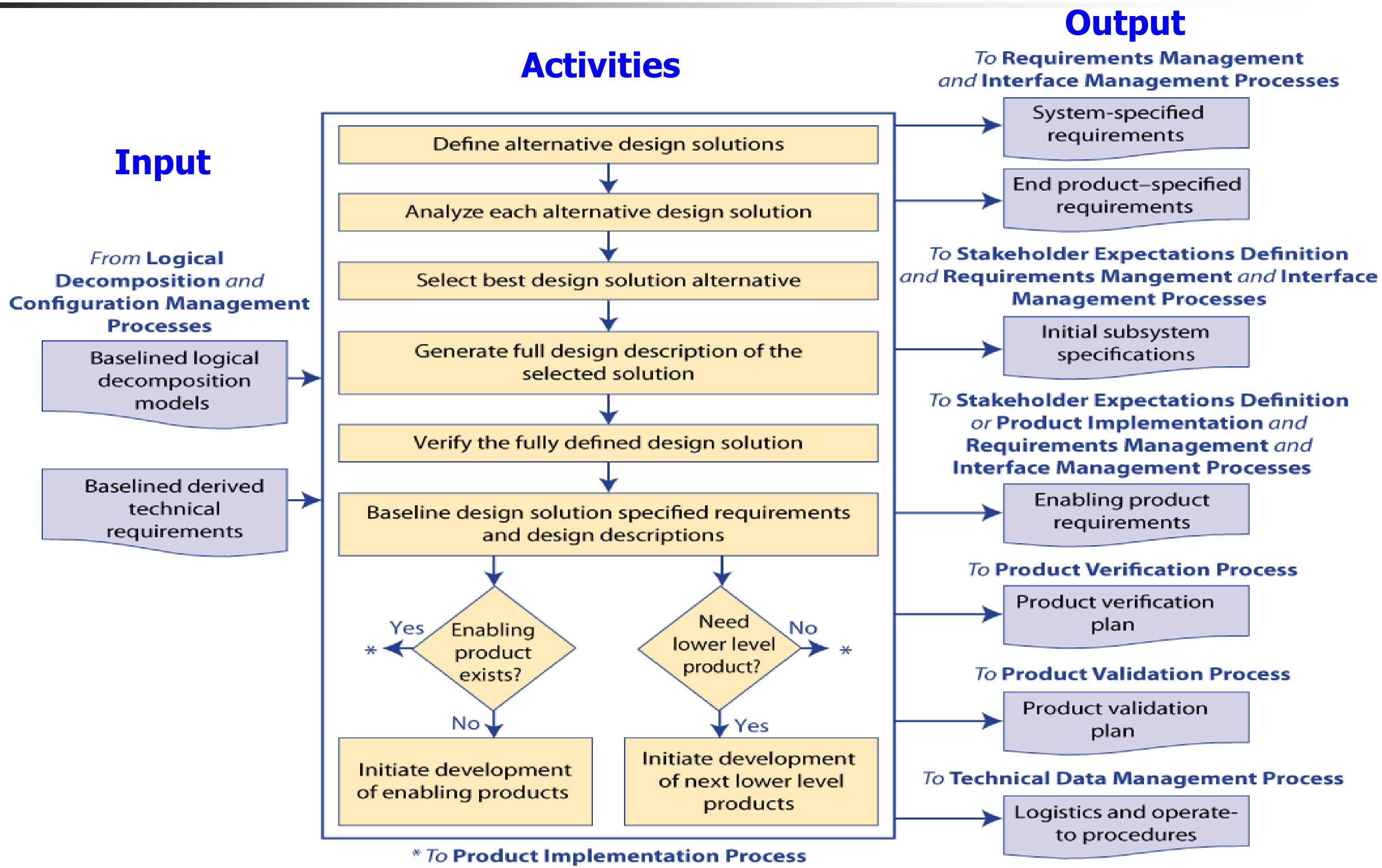
What we wanted

This image of a space shuttle has been removed due to copyright restrictions.

What we got

This image of a space shuttle in a building complex has been removed due to copyright restrictions.

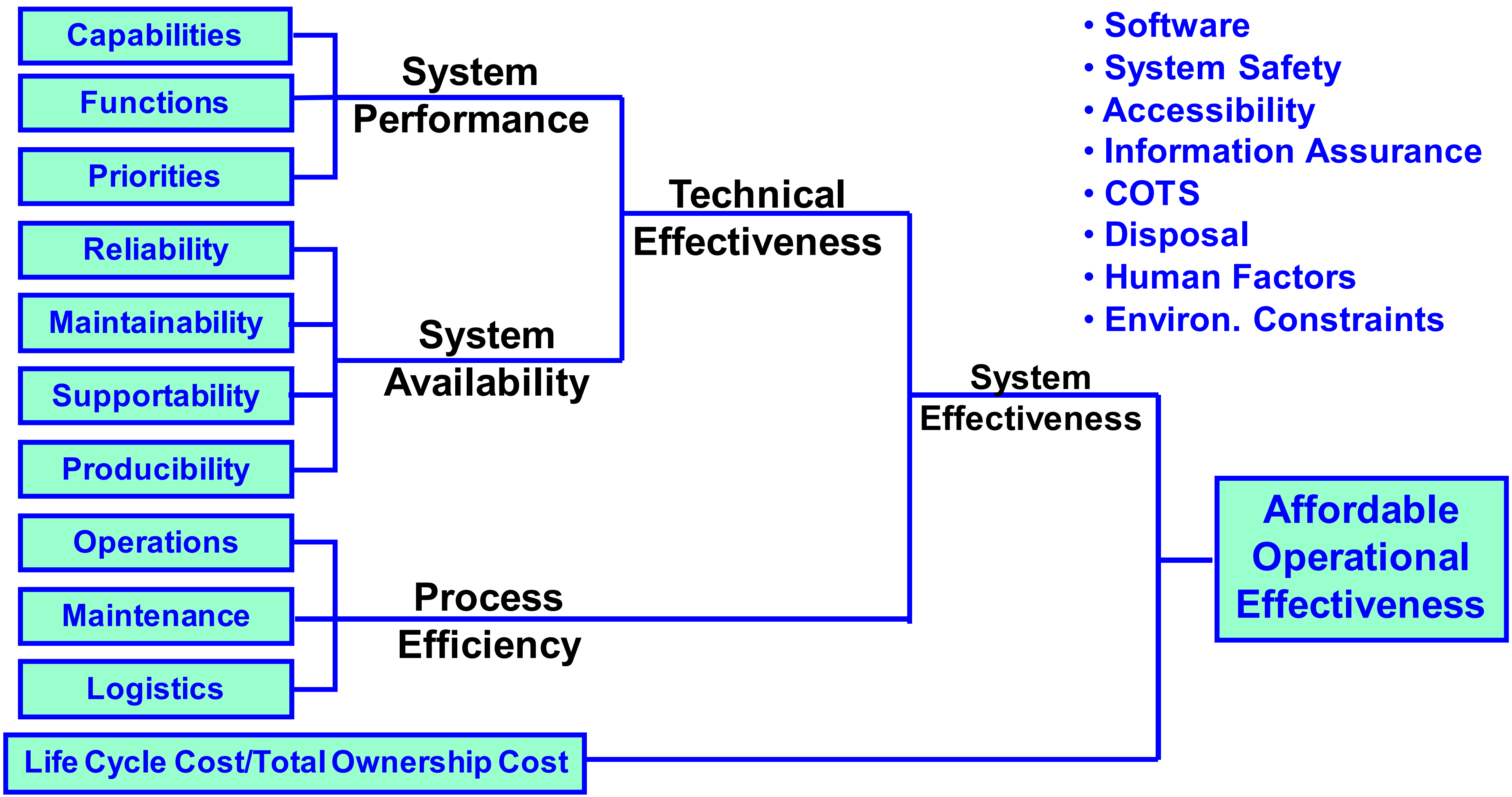
Design Solution Definition – Best Practice Process Flow Diagram



Design Solution Definition – Methods

- Analyzing each alternative to be able to select the preferred alternative
- Once an alternative is selected or baselined, the Design Solution Definition Process will be used for:
  - Generating end products as a function of the hierarchy in the system structure
- The output end product Design Solution Definition will be used for conducting product verification

Design Solution Definition – Important Design Considerations



Other Considerations
- Software
- System Safety
- Accessibility
- Information Assurance
- COTS
- Disposal
- Human Factors
- Environ. Constraints

Design Solution Definition – Summary

- The Design Solution Definition Process is used to translate the outputs of the Logical Decomposition Process into a design solution definition
- Alternative design solutions must be defined and analyzed to select the best alternative that satisfies technical requirements
- The form of the design solution definition depends on the product life cycle phase and its hierarchy in the system
- The Technical Data Package allows for the building, coding, reusing, or buying of products

Outline

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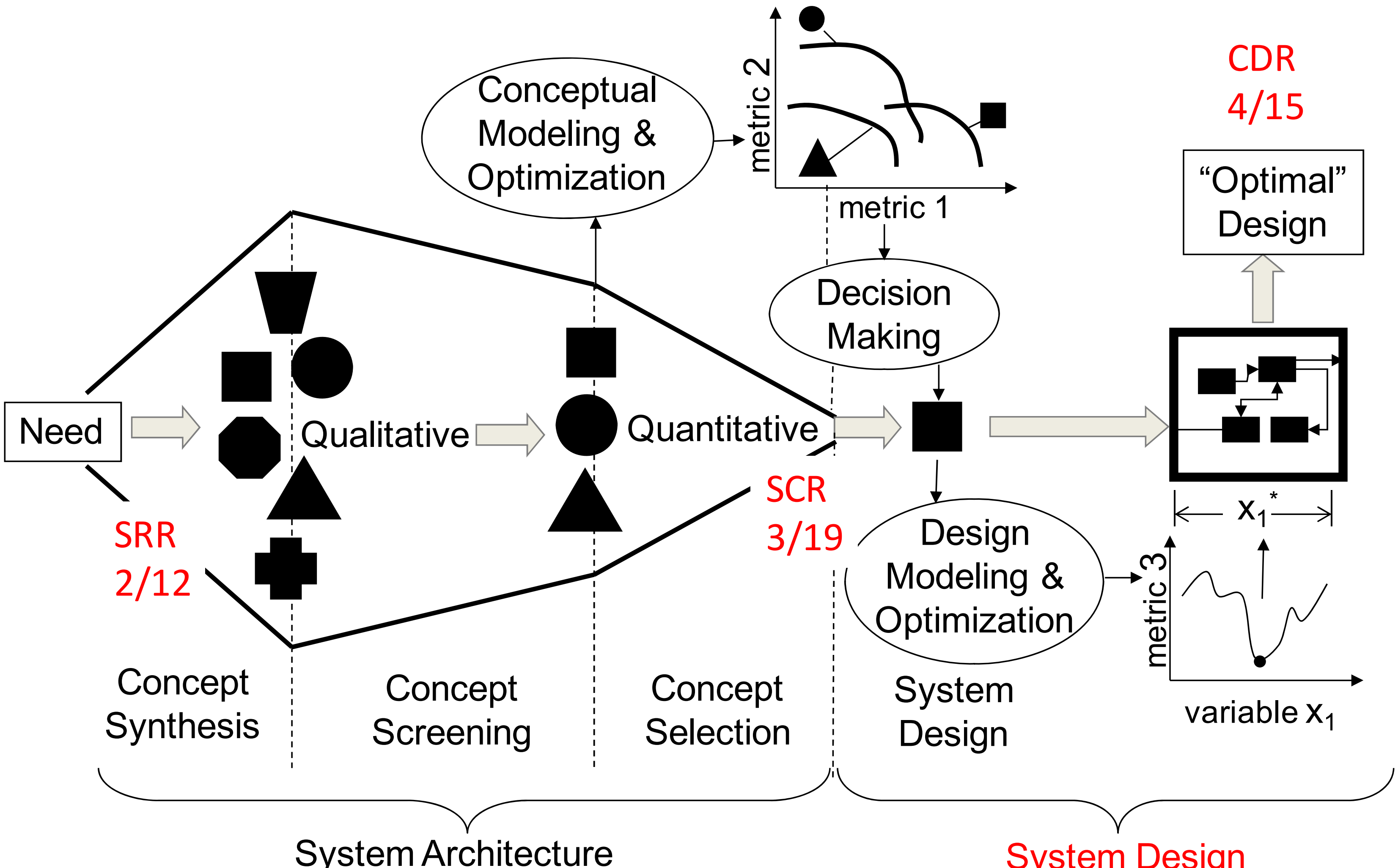
  - What it is and where it fits in…
  - Roots
  - Motivation
  - Method
  - Limitations
  - Future Trends
- Some MDO Applications

Multidisclinary Design Optimization (MDO) – What it is and where it fits in…

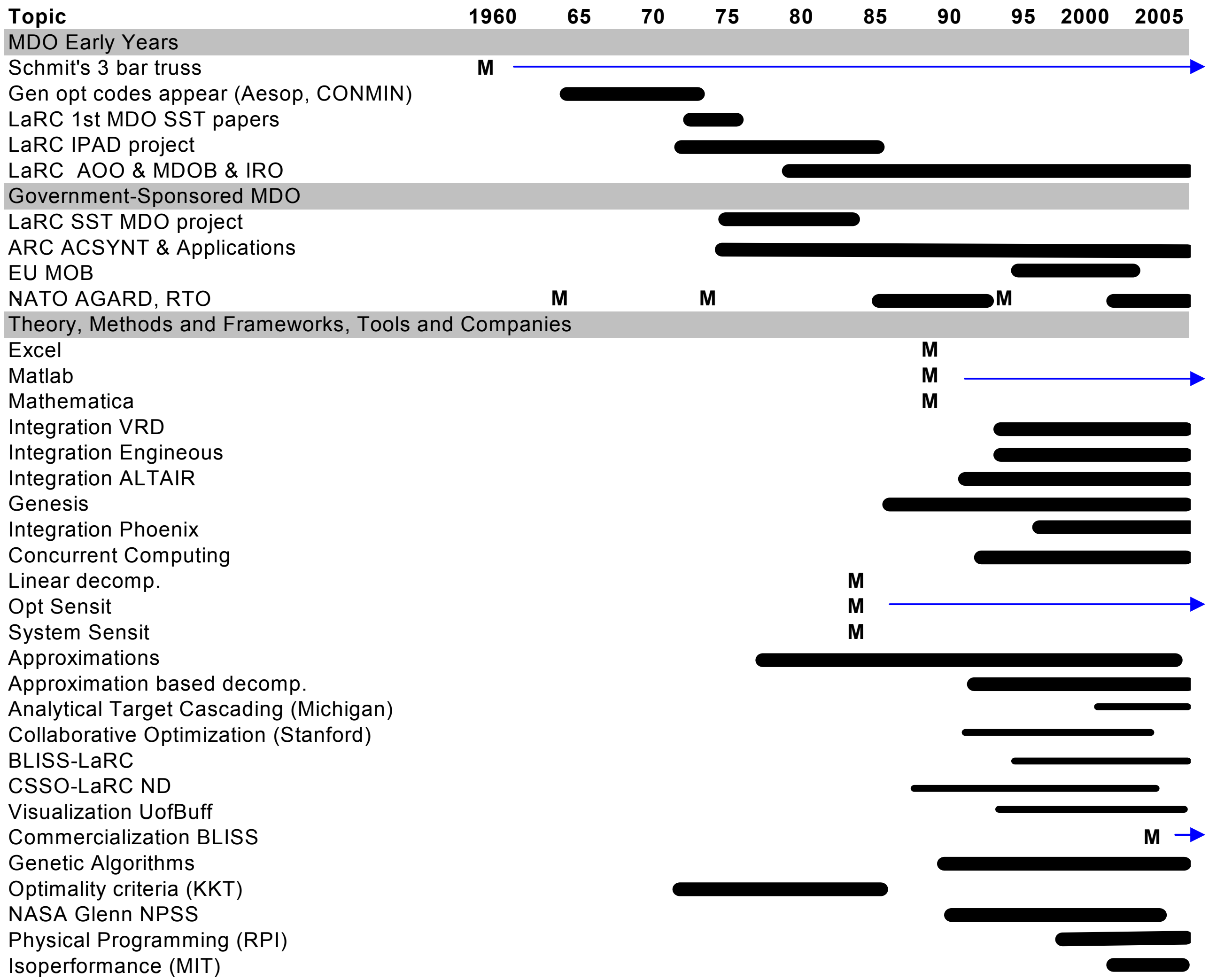
- MDO defined as *(AIAA MDO Tech Committee):*
  - "an evolving methodology, i.e. a body of methods, techniques, algorithms, and related application practices, for design of engineering systems couple by physical phenomena and involving many interacting subsystems and parts."
  - *Emphasis*: 1) still evolving, 2) involves many disciplines
- Conceptual Components of MDO *(Sobieksi '97)*
  - Mathematical Modeling of a System
  - Design Oriented Analysis
  - Approximation Concepts
  - System Sensitivity Analysis (less so w/ some methods)
  - Classical Optimization Procedures
  - Human Interface

Multidisclinary Design Optimization (MDO) – What it is and where it fits in…



Source: NASA Langley

MDO - Roots



MDO roots found in structural optimization

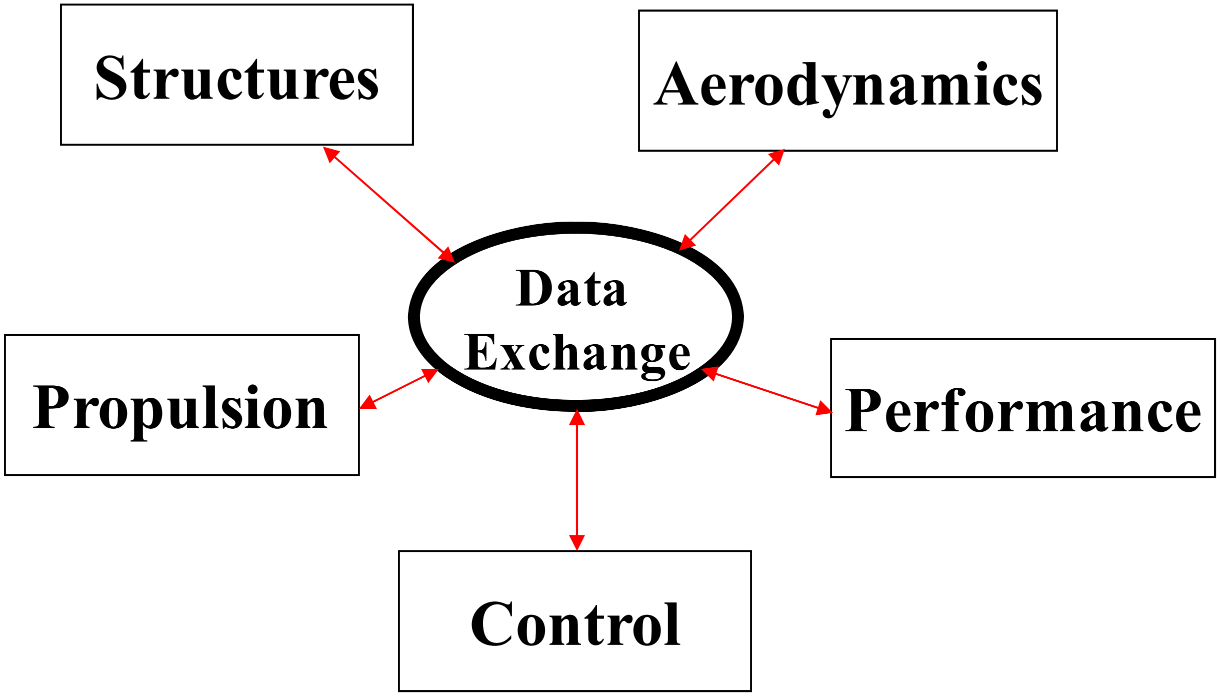
Optimization algrthms in mainstream prgms

More complex decomposition techniques appear

Commercialization of multi-level algorithm

MDO - Motivation

- Design systems are very complex and interconnected



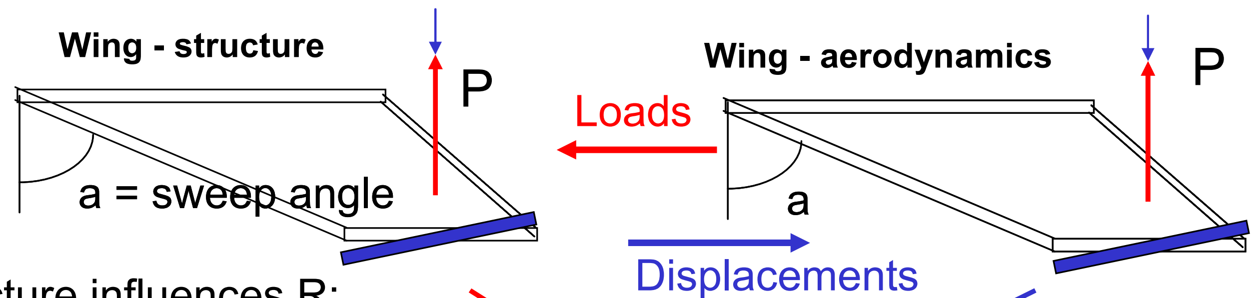
"Everything affects everything else"

Source: NASA Langley

MDO - Motivation

- Simple example of interdependency

Range (R) is the system objective



- Structure influences R:
  - directly by weight
  - indirectly by stiffness that affect displacements that affect drag

Loads & Displacements must be consistent

$$R = (k/Drag)\ LOG\ [(W_o + W_s + W_f)/(W_o + W_s)]$$

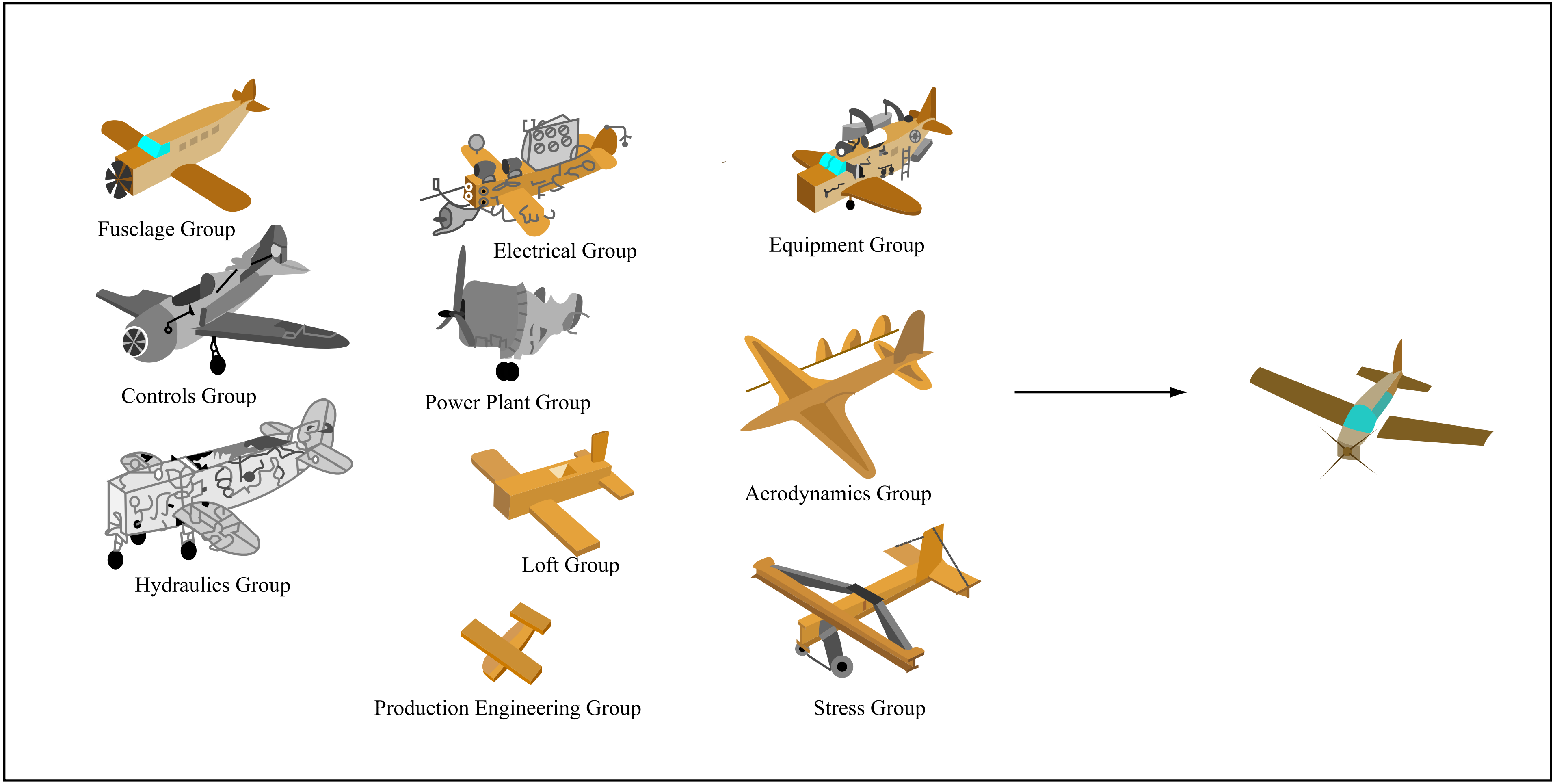
- **What to optimize the structure for? Lightness?**
  Displacements = 1/Stiffness?
  An optimal mix of the two?

Source: NASA Langley

MDO - Motivation

- Today's design systems are subject to very stringent contraints
  - **Cost**: the more complex the system is -> the more expensive
  - **Time**: USAF (field as fast as possible), NASA (replace aging space systems)
  - **Environment**: Aircraft noise restrictions, Auto exhaust, Improve fuel efficiency (minimum weight, max efficient engines)
- Further constrained in that these systems require large groups of people with a broad range of expertise
  - Design teams divided into specialty groups
  - These teams generally geographically seperated
  - Teams prefer to optimize (design) in own expertise domain
  - But their domains remain coupled by data exchange

MDO - Motivation



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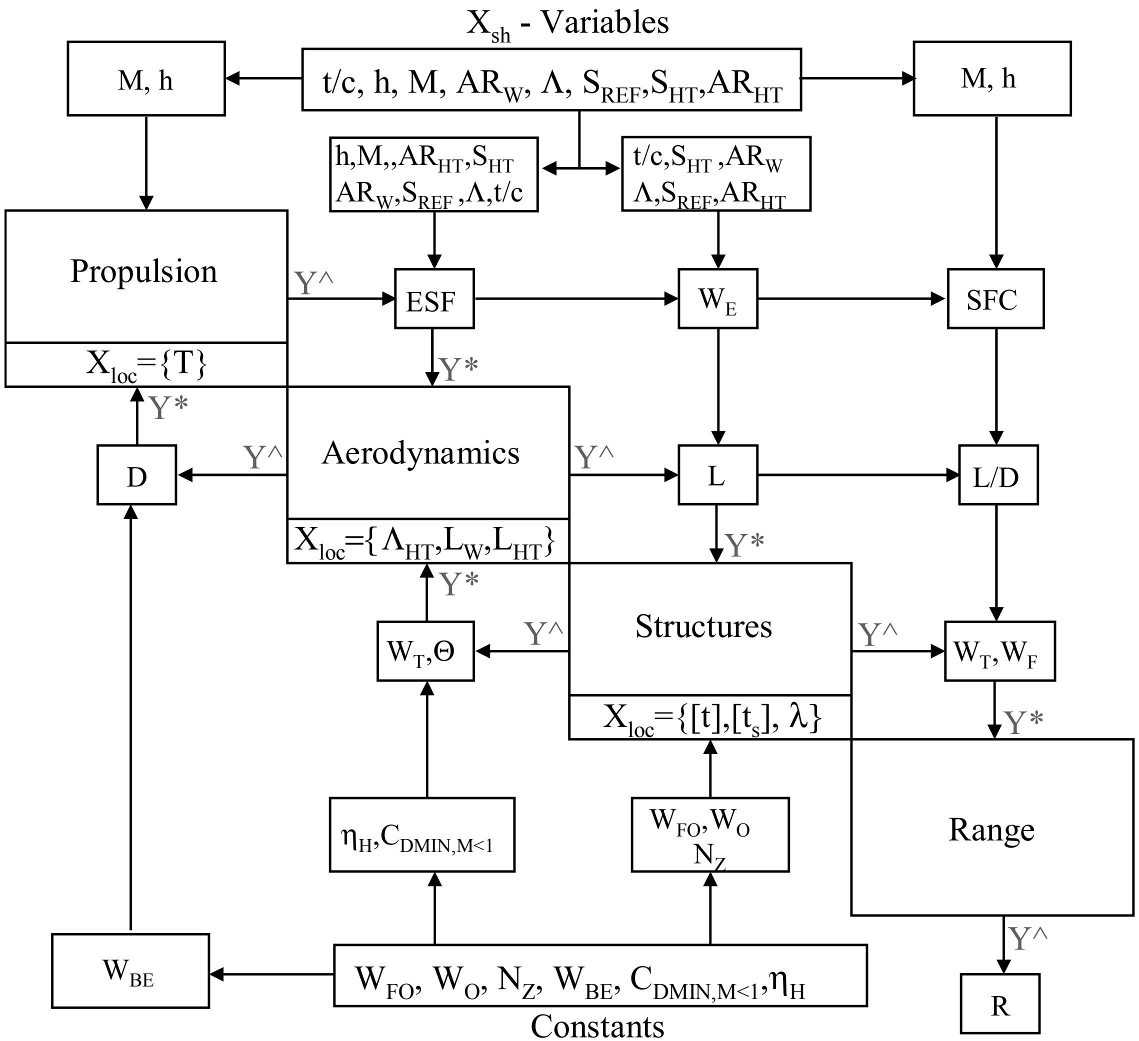
MDO helps us get from this… …to this…

…and still fully utilize all of today's modern computational tools.

MDO - Method

(1) Define overall system requirements
(2) Define design vector **x**, objective **J** and constraints **g, h**
(3) System decomposition into modules
(4) Modeling of physics via governing equations at the module level - module execution in isolation
(5) Model integration into an overall system simulation
(6) Benchmarking of model with respect to a known system from past experience, if available
(7) Design space exploration (DOE) to find sensitive and important design variables x_i
(8) Formal optimization to find min J(x)
(9) Post-optimality analysis to explore sensitivity and tradeoffs: sensitivity analysis, approximation methods, isoperformance, include uncertainty

MDO – Method: Bi-Level Integrated System Synthesis



X_{LOC}:
- T-throttle
- Λ_{HT}- tail sweep
- L_W-wing mom. arm
- L_{HT}-tail mom. arm
- [t]-thickness array, size 1x9
- [t_S]-thickness array, size 1x9
- λ-taper ratio

Y:
- D-drag
- ESF-eng. scale fact.
- L-lift
- N_Z-max. load fact.
- R-range
- SFC-spec. fuel cons.
- Θ-wing twist
- W_E-engine weight
- W_F-fuel weight
- W_T-total weight

X_{SH}:
- AR_W- wing aspect ratio
- AR_{HT}- tail aspect ratio
- h-altitude
- M-Mach #
- S_{REF}-wing surf. area
- S_{HT}-tail surf. area
- t/c-thickness/chord
- Λ_W-wing sweep

MDO – Method: Bi-Level Integrated System Synthesis

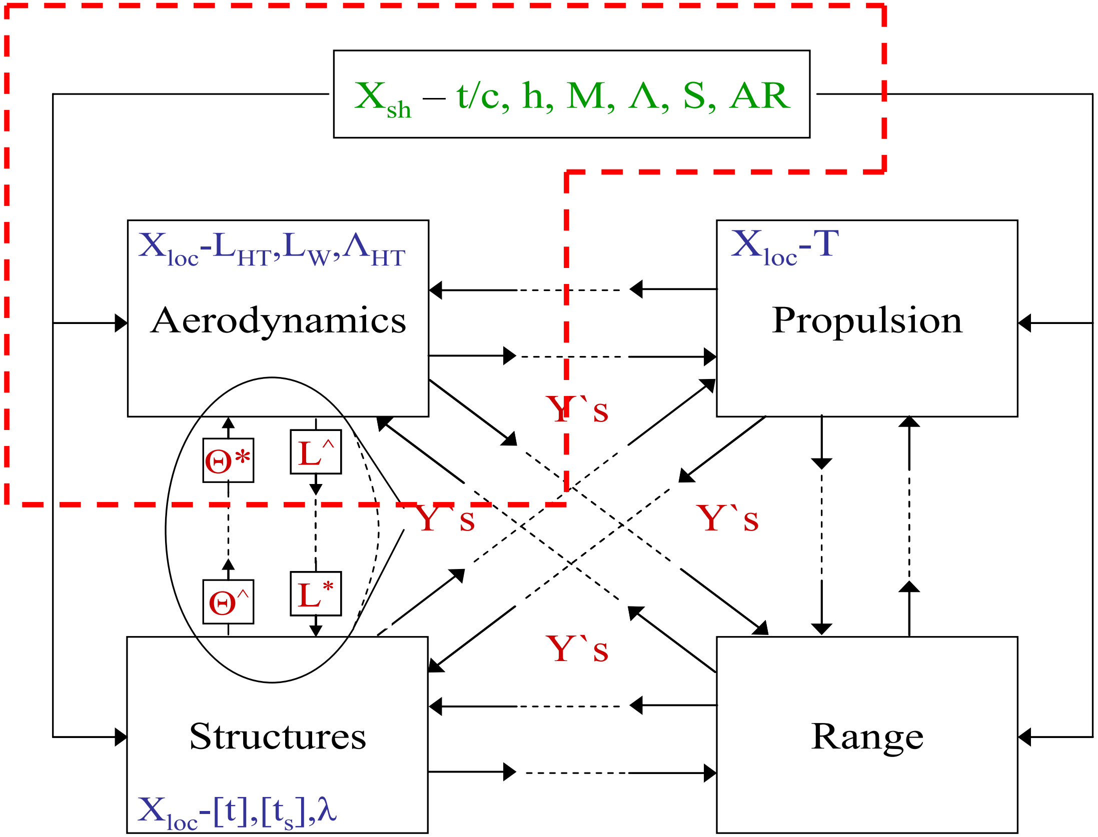
- Formulation of Design System: Supersonic Business Jet Example

X_{sh}-design variable shared by at least two subsystems

X_{loc}-design variable unique to a specific subsystem

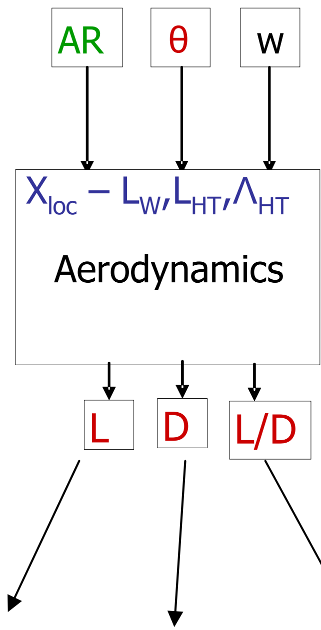
Y*-coupling variable input to particular subsystem

Y^-coupling variable output from a particular subsystem



MDO – Method: Bi-Level Integrated System Synthesis

- Subsystem Optimization (SSOPT)



➢ SSOPT Formulation

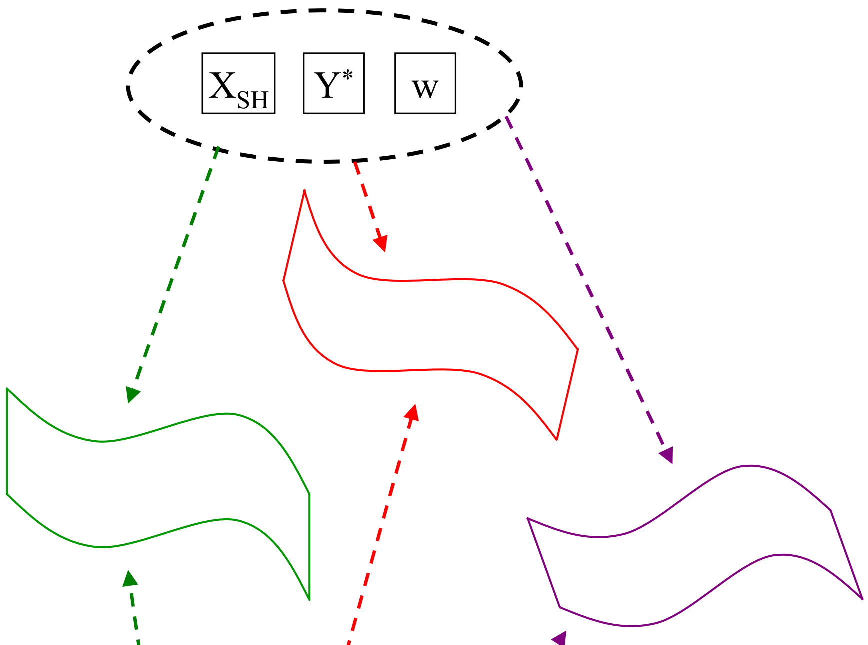
Given: $Q = \{[X_{sh}],[Y^*],[w]\}$,
minimize: $f(\ w,\ Y\hat{}(X_{loc},\ X_{sh},\ Y^*))$
by varying: $[X_{loc}]$.
Satisfy: $g(X_{loc}) \leq 0$
$h(X_{loc}) = 0$ and
$[X_{loc,LB}] \leq [X_{loc}] \leq [X_{loc,UB}]$,
and retrieve: $[X_{loc}]$ and $[Y\hat{}]$ at optimum

$$f = w_1 Y\hat{}_1 + w_2 Y\hat{}_2 + w_3 Y\hat{}_3 = \sum_{i=1}^{n} w_i Y_i\hat{}$$

where n = # of Y^ outputs

MDO – Method: Bi-Level Integrated System Synthesis

- Subsystem Optimization (SSOPT)



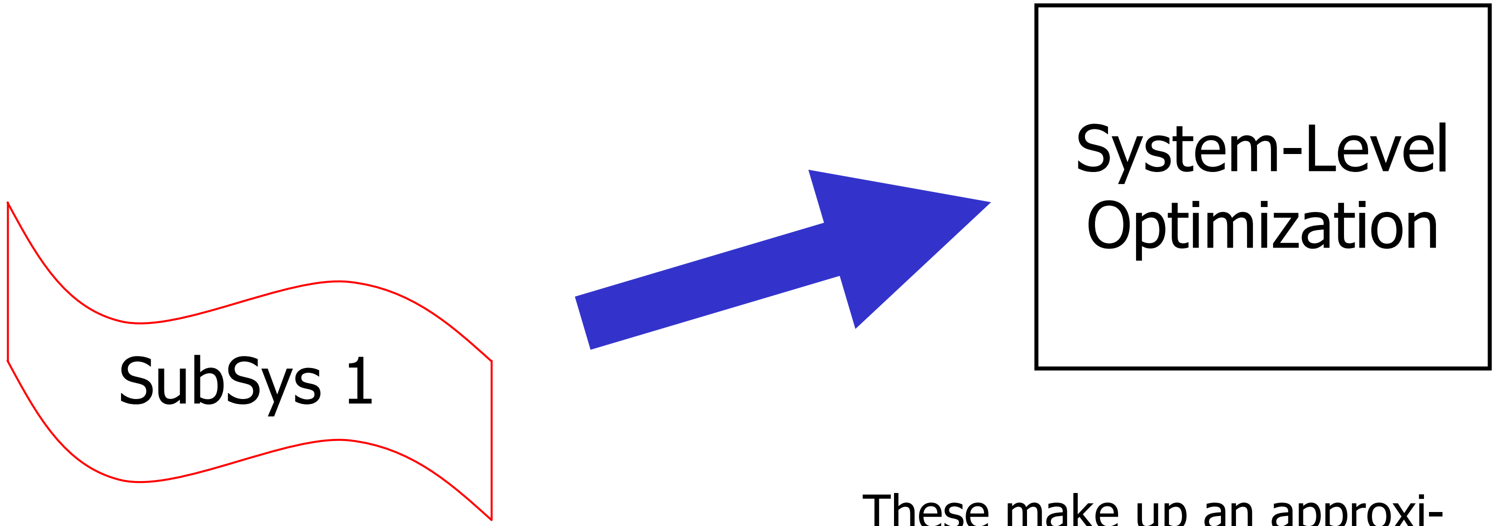
$$f = w_1 Y^{\wedge}_1 + w_2 Y^{\wedge}_2 + w_3 Y^{\wedge}_3 = \sum_{i=1}^{n} w_i Y_i^{\wedge}$$

where n = # of Y^ outputs

Have series of approximation models, one for each Y^ output

MDO – Method: Bi-Level Integrated System Synthesis

- Subsystem Optimization (SSOPT)

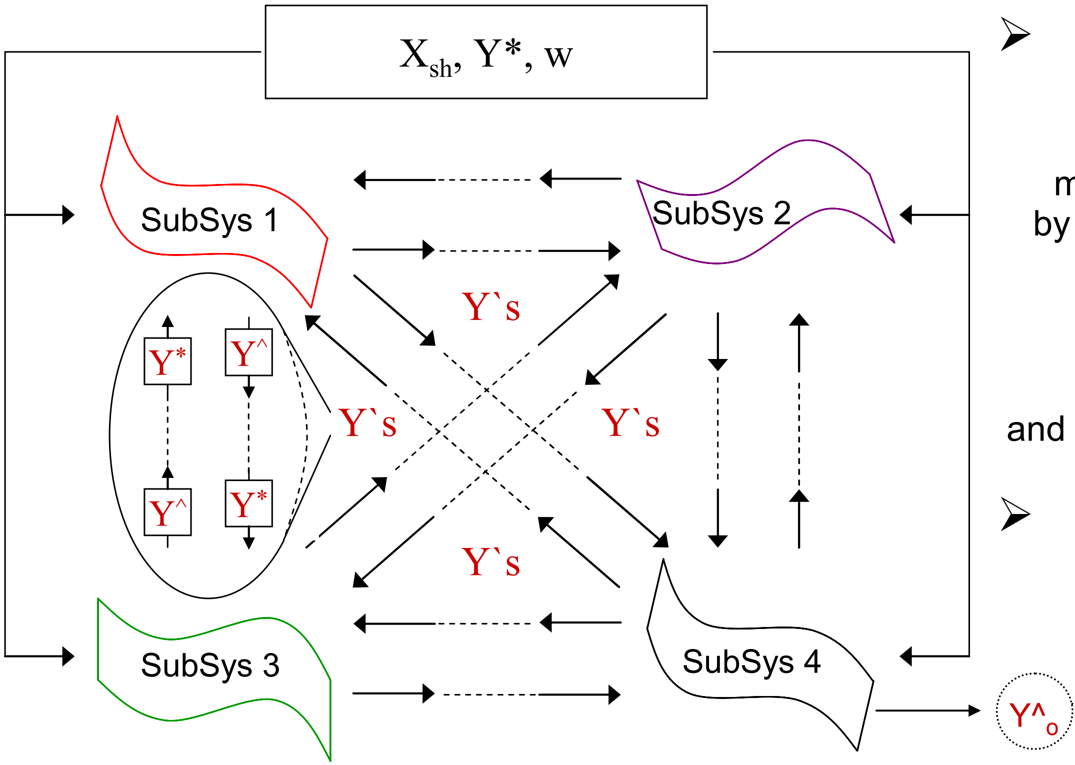


These make up an approxi-mated subsystem…

…which is then sent to the system-level optimization.

MDO – Method: Bi-Level Integrated System Synthesis

- System Optimization (SOPT)



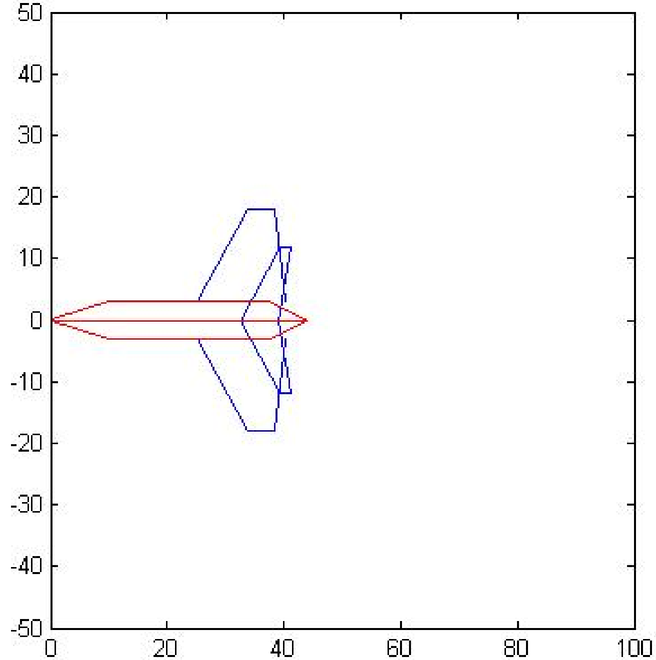
- SOPT Formulation

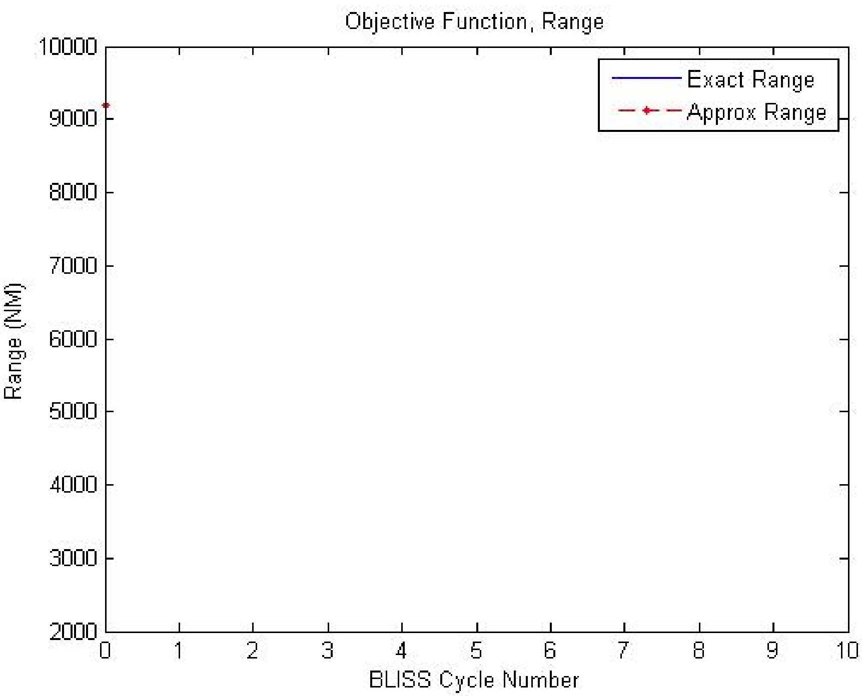
Given: approximation models for optimized subsystem outputs,
minimize: F (X_{sh}, Y^*, w),
by varying: Q = {[X_{sh}],[Y^*],[w]}.
Satisfy: c = [Y^*]-[$Y^\wedge$] = 0,
[$X_{sh,LB}$] ≤ [X_{sh}] ≤ [$X_{sh,UB}$],
[Y^*_{LB}] ≤ [Y^*] ≤ [Y^*_{UB}], and
[w_{LB}] ≤ [w] ≤ [w_{UB}],
and retrieve: [X_{sh}],[Y^*],[w], and F at optimum

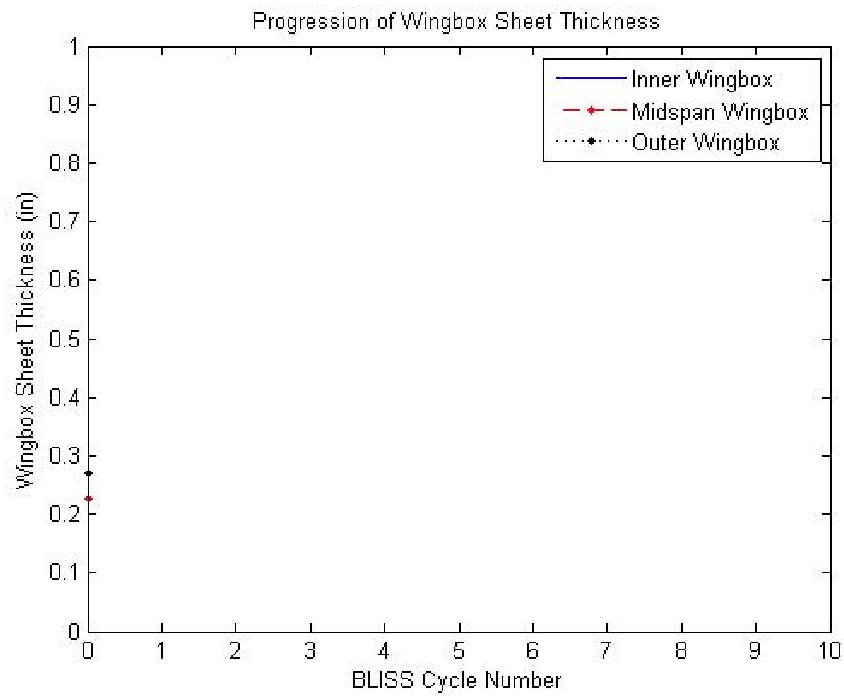
- SOPT Objective Function

$$F = Y_o^\wedge$$

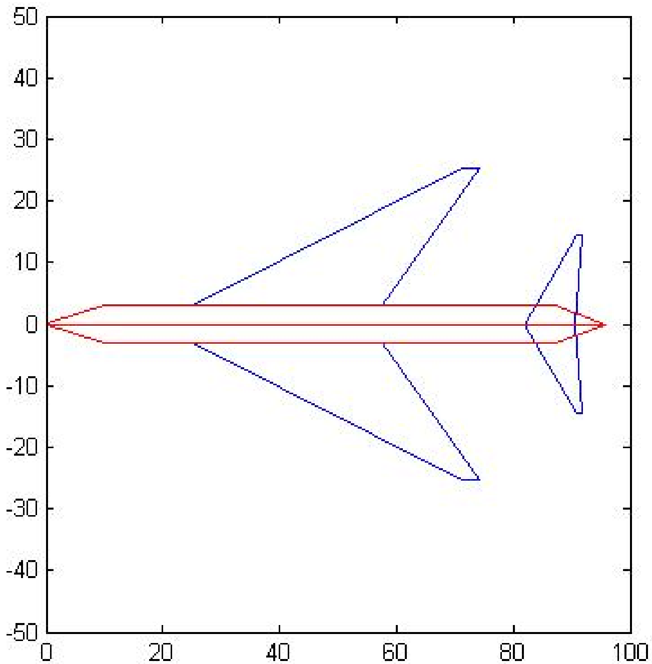
BLISS Cycle # 0

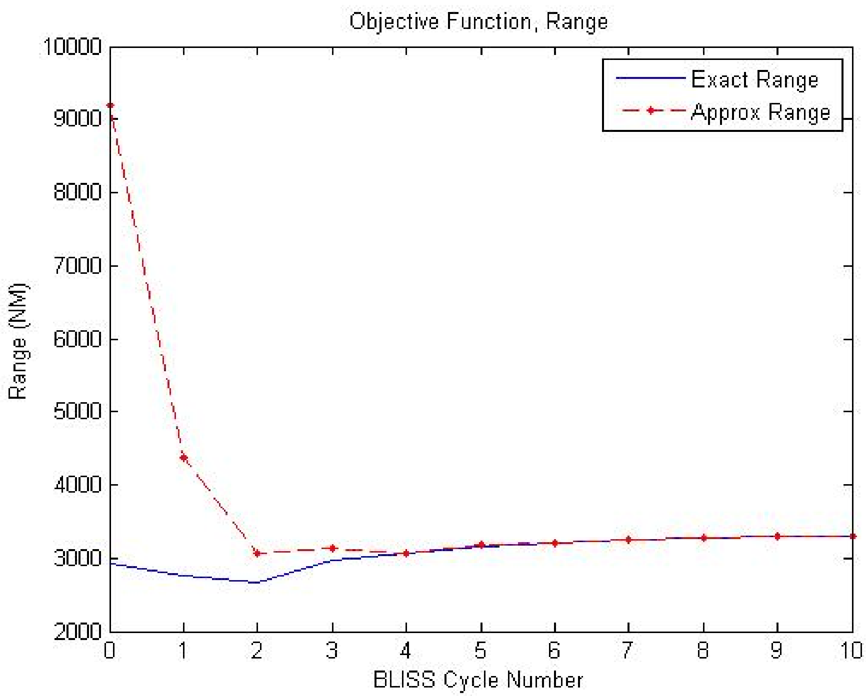


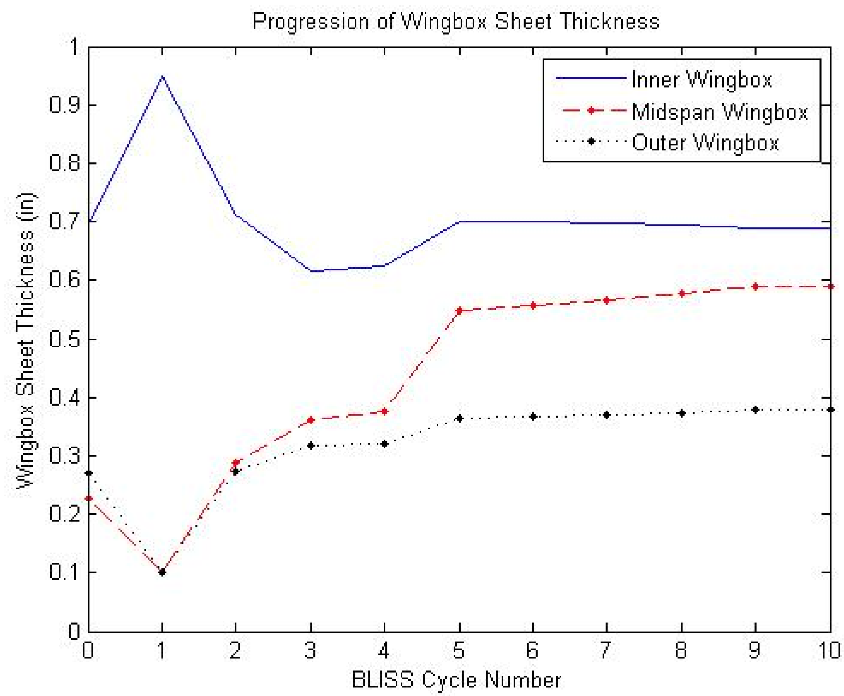




BLISS Cycle # 10







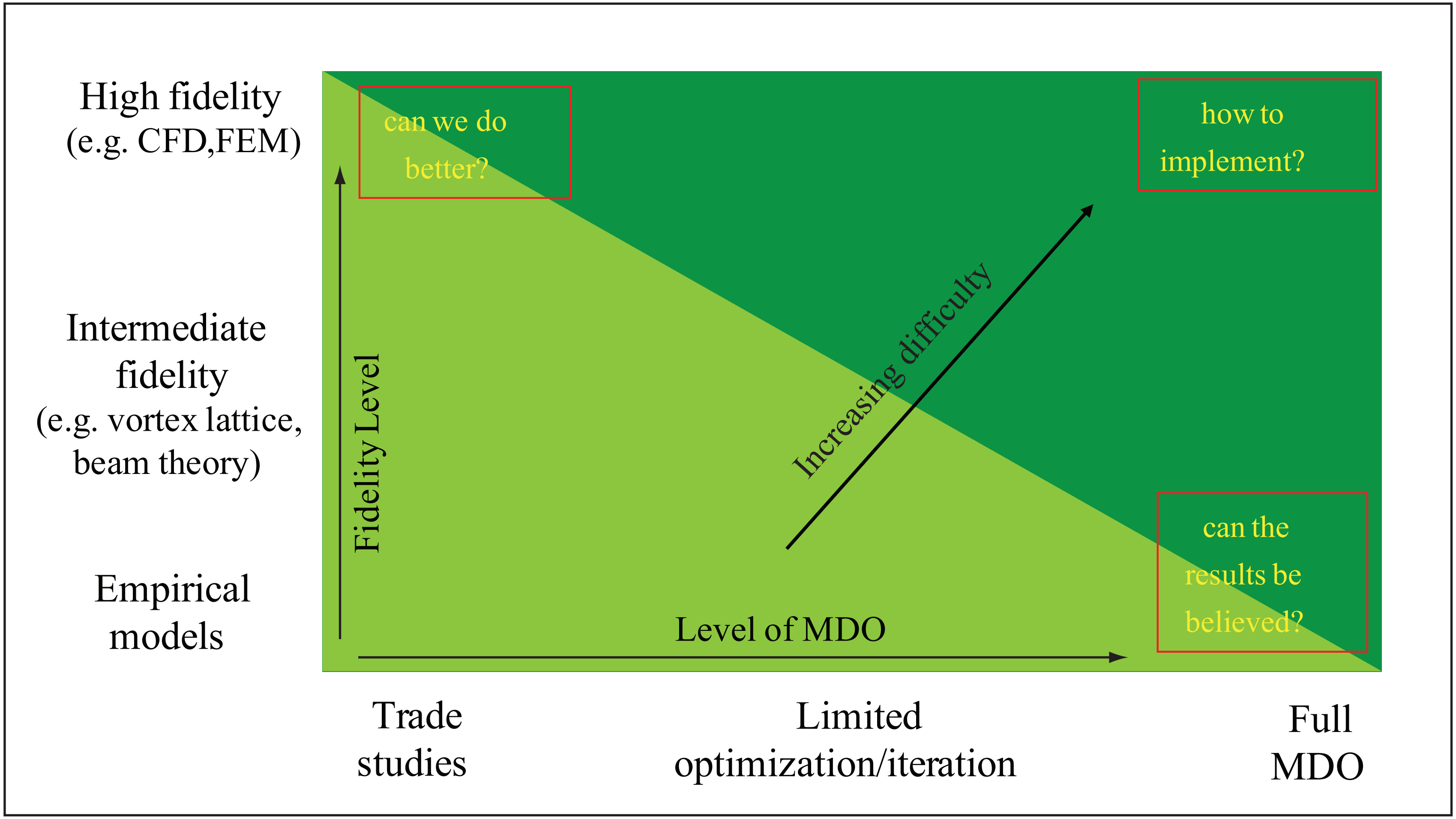
MDO - Challenges

- Fidelity/expense of disciplinary models
  Fidelity is often sacrificed to obtain models with short computation times.
- Complexity
  Design variables, constraints and model interfaces must be managed carefully.
- Communication
  The user interface is often very unfriendly and it can be difficult to change problem parameters.
- Flexibility
  It is easy for an MDO tool to become very specialized and only valid for one particular problem.

How do we prevent MDO codes from becoming complex, highly specialized tools which are used by a single person (often the developer!) for a single problem?

MDO - Challenges

Fidelity vs. Expense



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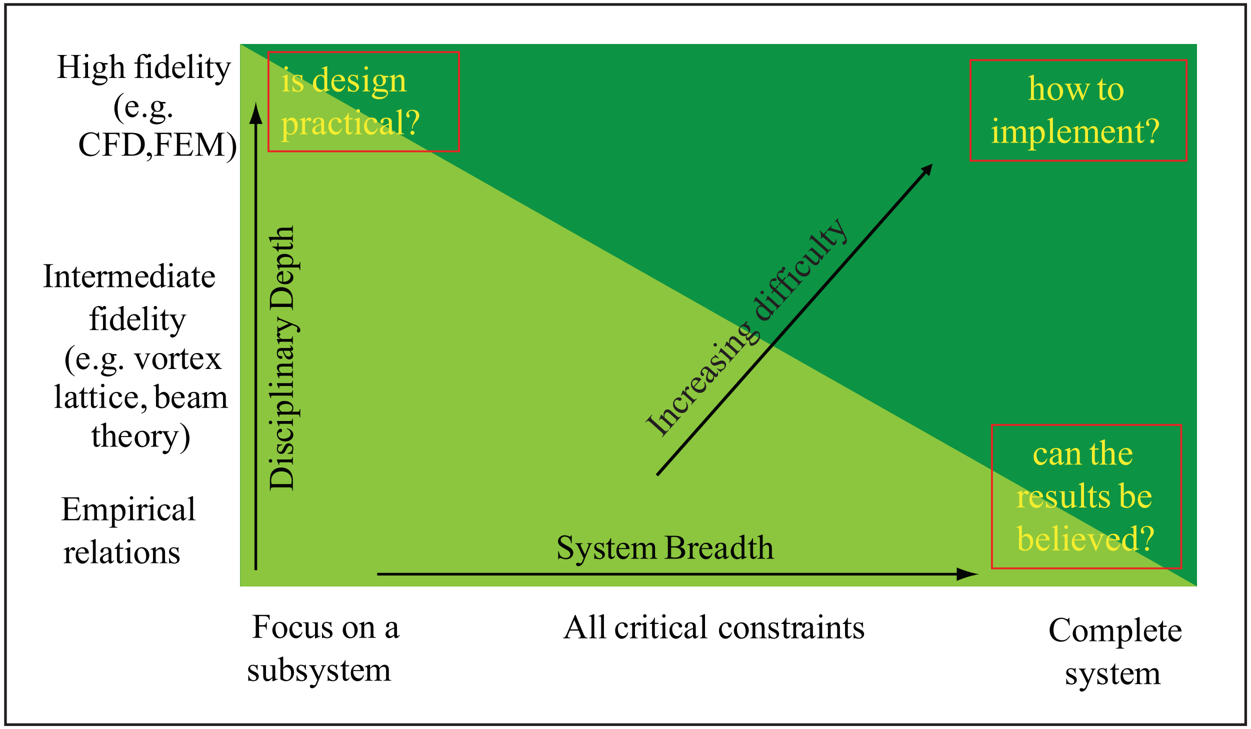
from Giesing, 1998

MDO - Challenges

Breadth vs. Depth



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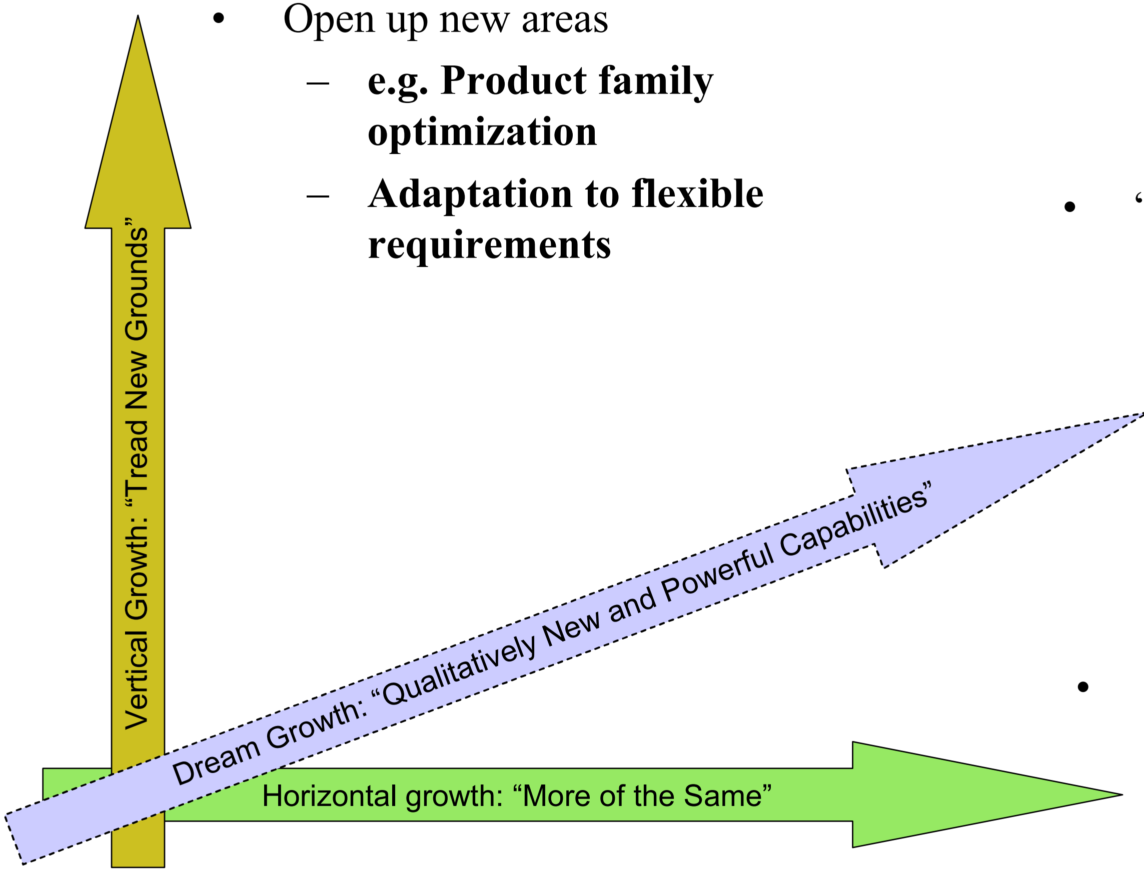
MDO – Future Trends

- Open up new areas
  - **e.g. Product family optimization**
  - **Adaptation to flexible requirements**

- “Dream Growth”
  - **Utopian**
  - **Long Term**



- Deepen current areas
  - **Increase dimensionality**
  - **Extend applications**

MDO - Summary

- Multi-Disciplinary Optimization is a rapidly developing engineering discipline
  - Still evolving
  - Requires a paradigm shift from traditional design practices
- Several methods are available for use in MDO
  - Choice of method depends on design problem
  - Nearly all can still be further improved
- Newfound applications for MDO are multiplying quickly
  - Modeling the design system often the significant challenge
  - Rapid increases in computing power greatly enhance MDO capability
- Future developments are directed in two orthogonal, but mutually reinforcing directions
  - Horizontal for more capability
  - Vertical for new and innovative solutions

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