Massachusetts Institute of Technology

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Fundamentals of Systems Engineering

Prof. Olivier L. de Weck

Session 6

Design Definition

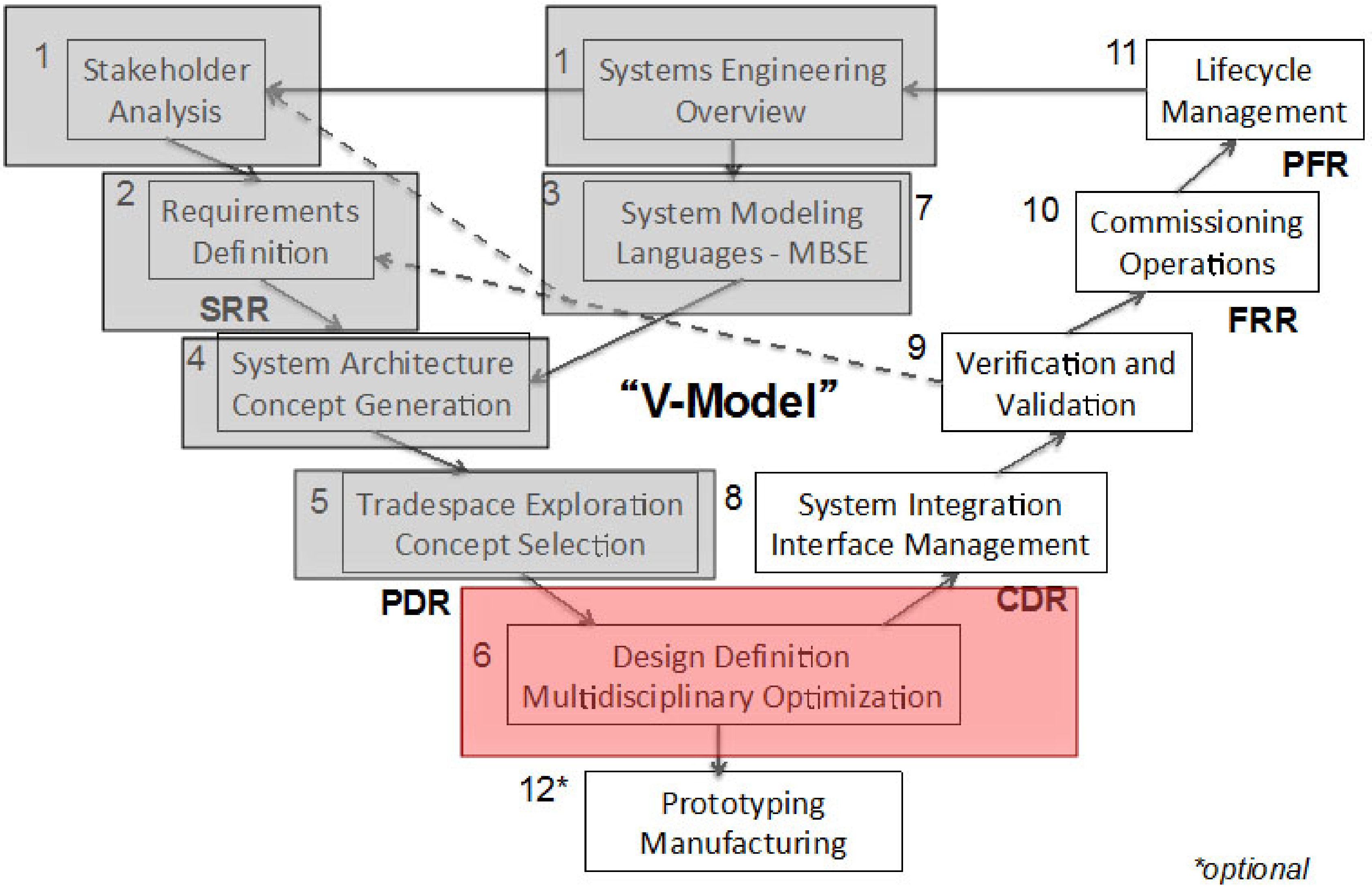
Multidisciplinary Optimization

A3 is due today ! A4 is due on Nov 6.

Assignment	*Topic*	*Weight*
A1 (group)	Team Formation, Definitions, Stakeholders, Concept of Operations (CONOPS)	12.5%
A2 (group)	Requirements Definition and Analysis Margins Allocation	12.5%
A3 (group)	System Architecture, Concept Generation	12.5%
A4 (group)	Tradespace Exploration, Concept Selection	12.5%
A5 (group)	Preliminary Design Review (PDR) Package and Presentation	20%
Quiz (individual)	Written online quiz	10%
Oral Exam (individual)	20’ Oral Exam with Instructor 2-page reflective memorandum	10%

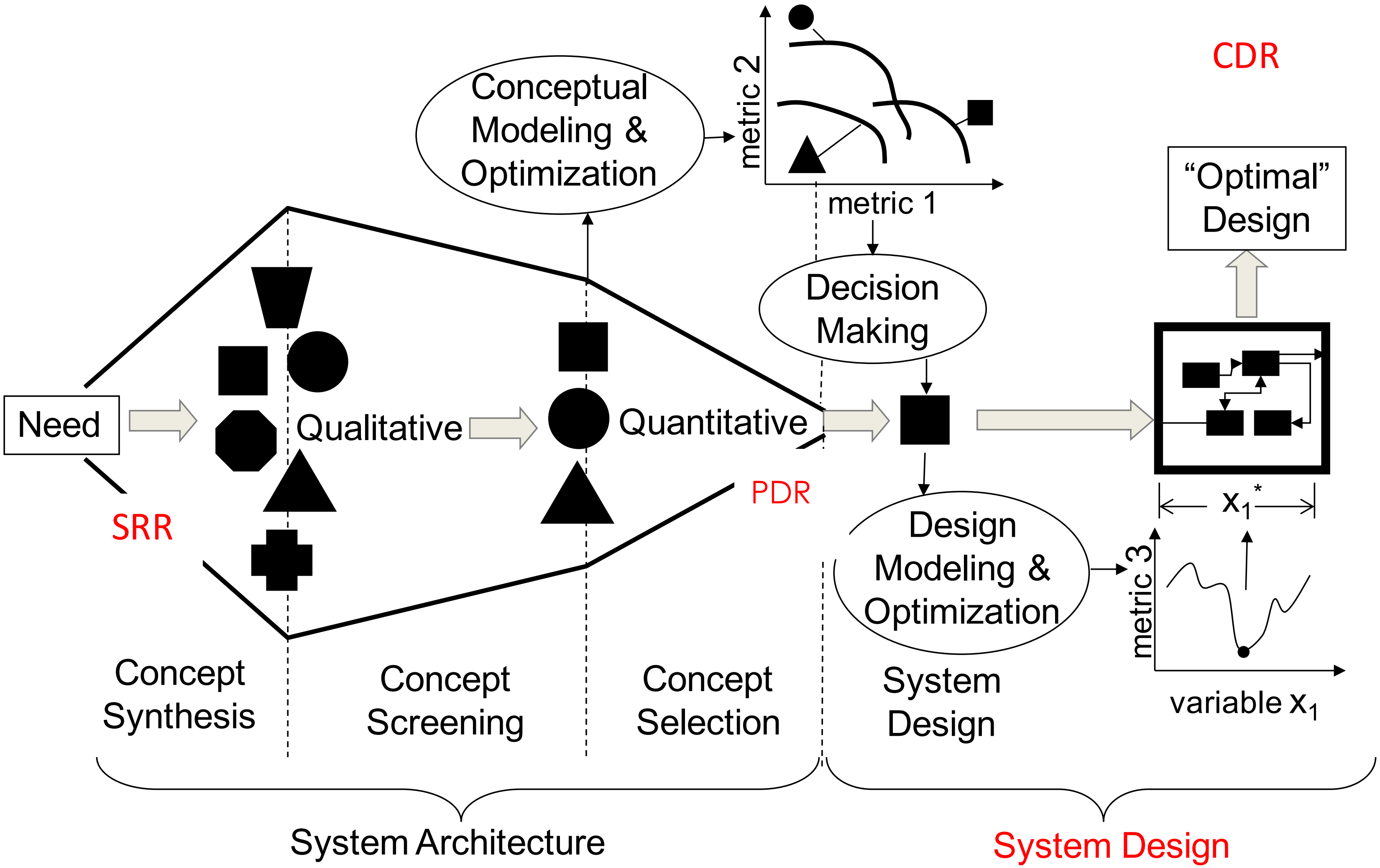
The "V-Model" of Systems Engineering

16.842/ENG-421 Fundamentals of Systems Engineering



Numbers indicate the session # in this class

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



Outline for today

- NASA Design Definition Process
  - Process Overview
- Multidisciplinary Design Optimization
  - What it is and where it fits in…
- Concurrent Design Facilities (CDF)
- Critical Design Review (CDR)

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

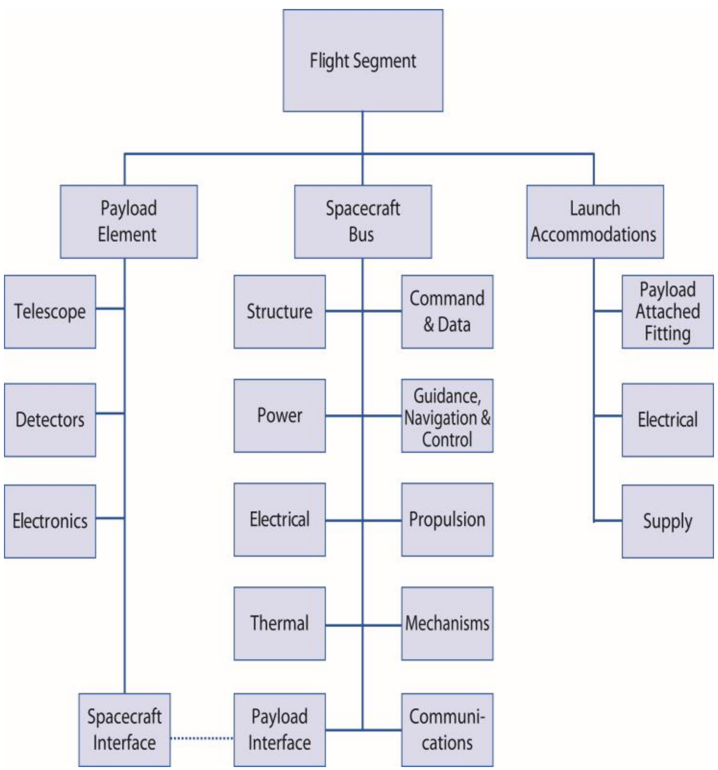
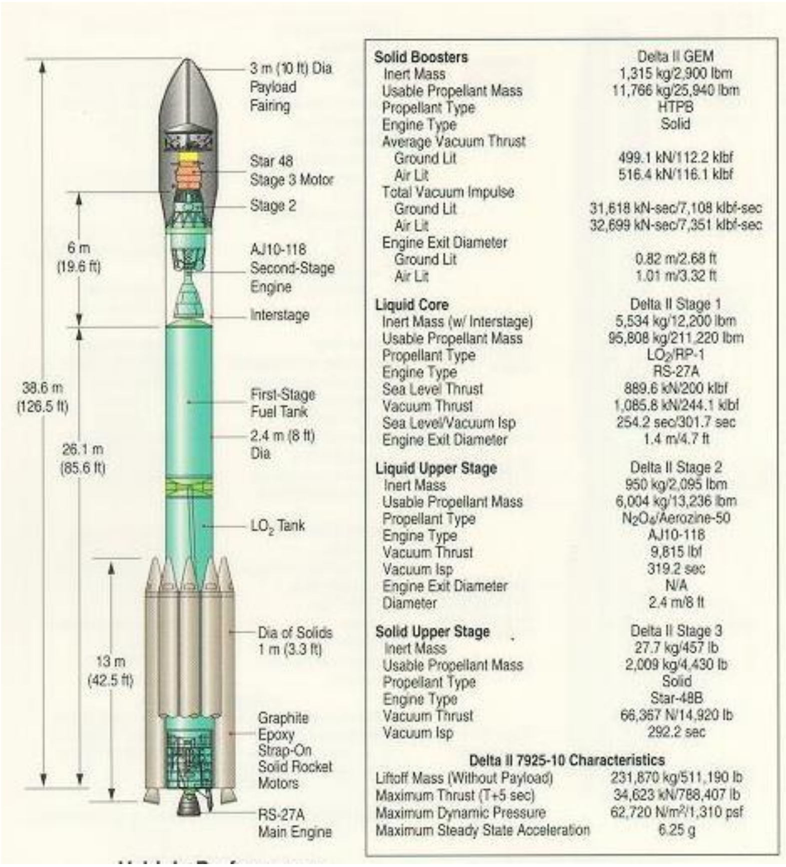


Figure 4.3-2 Example of a PBS

PBS = Product Breakdown Structure



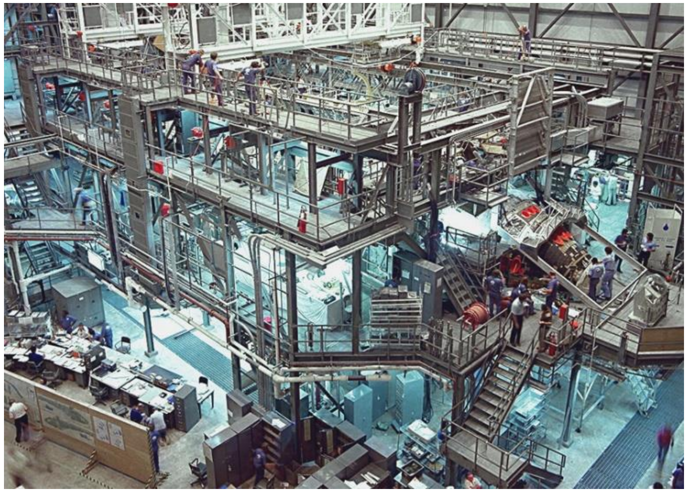
Solid Boosters	Delta II GEM
Inert Mass	1,315 kg/2,900 lbm
Usable Propellant Mass	11,766 kg/25,940 lbm
Propellant Type	HTPB
Engine Type	Solid
Average Vacuum Thrust	
Ground Lit	499.1 kN/112.2 klbf
Air Lit	516.4 kN/116.1 klbf
Total Vacuum Impulse	
Ground Lit	31,618 kN-sec/7,108 klbf-sec
Air Lit	32,699 kN-sec/7,351 klbf-sec
Engine Exit Diameter	
Ground Lit	0.82 m/2.68 ft
Air Lit	1.01 m/3.32 ft
Liquid Core	Delta II Stage 1
Inert Mass (w/ Interstage)	5,534 kg/12,200 lbm
Usable Propellant Mass	95,808 kg/211,220 lbm
Propellant Type	LO_2/RP-1
Engine Type	RS-27A
Sea Level Thrust	889.6 kN/200 klbf
Vacuum Thrust	1,085.8 kN/244.1 klbf
Sea Level/Vacuum Isp	254.2 sec/301.7 sec
Engine Exit Diameter	1.4 m/4.7 ft
Liquid Upper Stage	Delta II Stage 2
Inert Mass	950 kg/2,095 lbm
Usable Propellant Mass	6,004 kg/13,236 lbm
Propellant Type	N_2O_4/Aerozine-50
Engine Type	AJ10-118
Vacuum Thrust	9,815 lbf
Vacuum Isp	319.2 sec
Engine Exit Diameter	N/A
Diameter	2.4 m/8 ft
Solid Upper Stage	Delta II Stage 3
Inert Mass	27.7 kg/457 lb
Usable Propellant Mass	2,009 kg/4,430 lb
Propellant Type	Solid
Engine Type	Star-48B
Vacuum Thrust	66,367 N/14,920 lb
Vacuum Isp	292.2 sec
Delta II 7925-10 Characteristics	
Liftoff Mass (Without Payload)	231,870 kg/511,190 lb
Maximum Thrust (T+5 sec)	34,623 kN/788,407 lb
Maximum Dynamic Pressure	62,720 N/m²/1,310 psf
Maximum Steady State Acceleration	6.25 g

Design Solution Importance

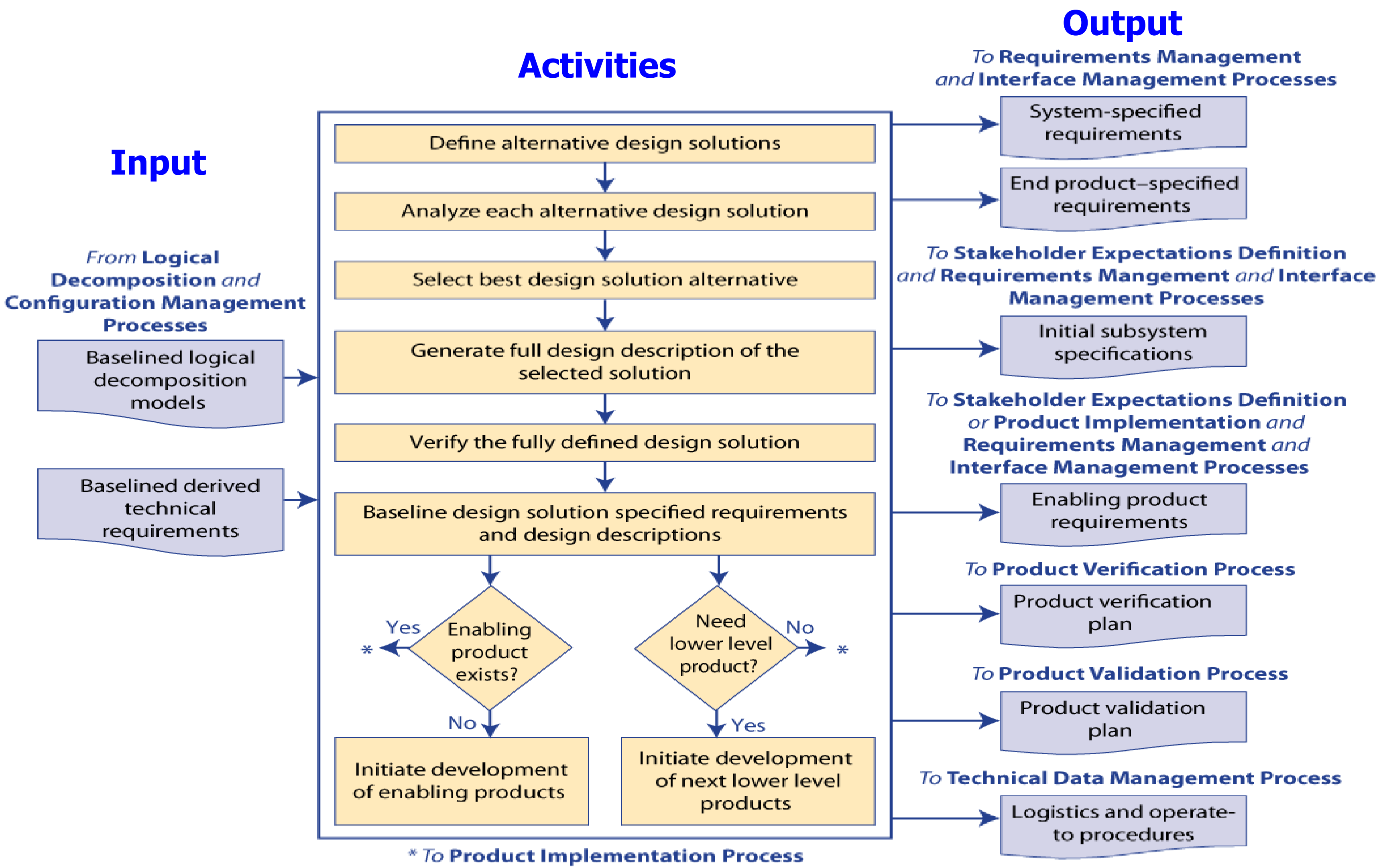
- Define solution space
- Develop design alternatives
- Trade studies to analyze
  - Alternate Design
  - Cost, performance, schedule
- Select Design Solution
- Drive down to lowest level
- Identify enabling products

What we wanted

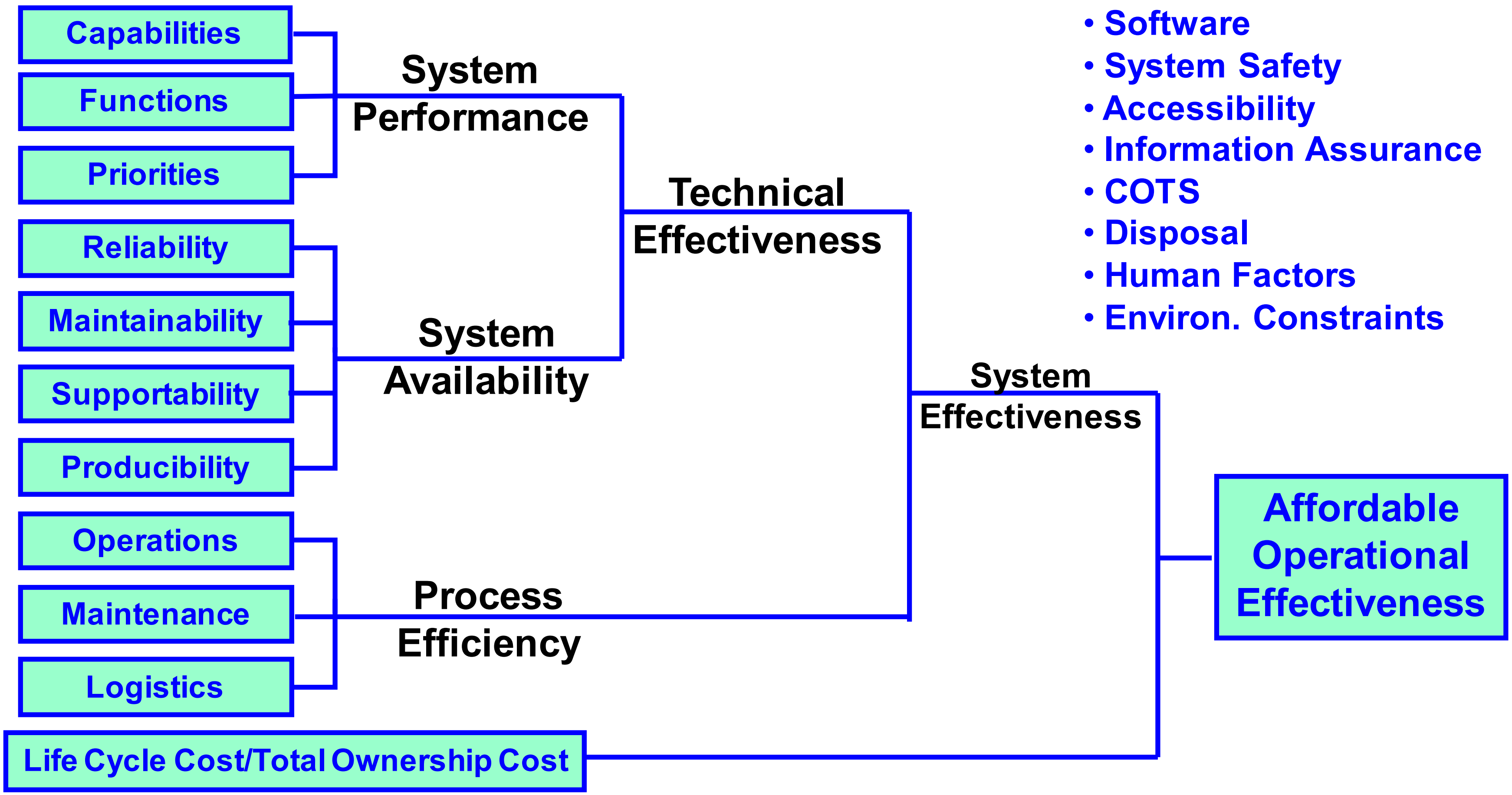
What we got



Design Solution Definition – Best Practice Process Flow Diagram



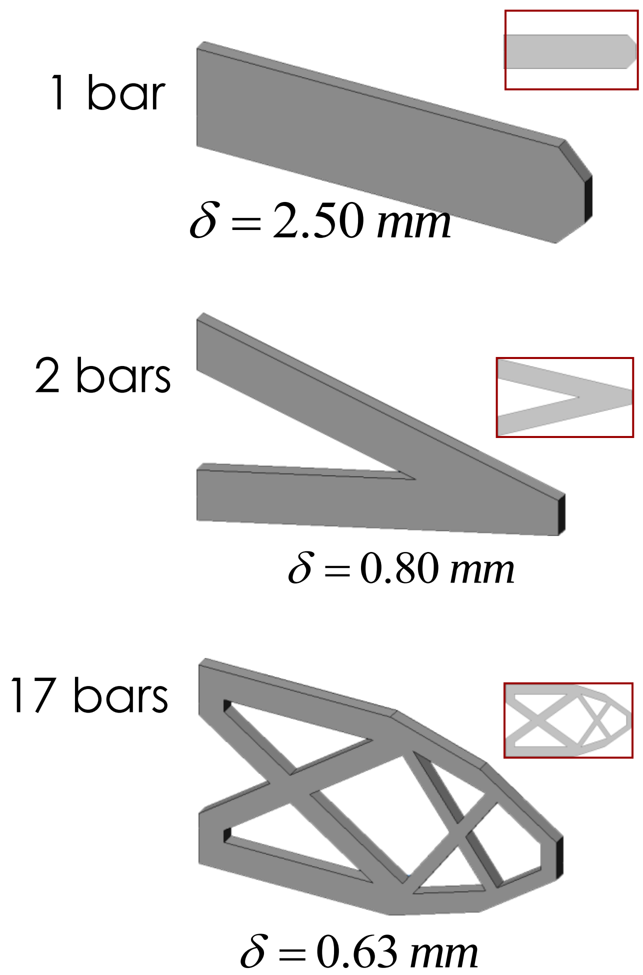
Design Solution Definition – Important Design Considerations

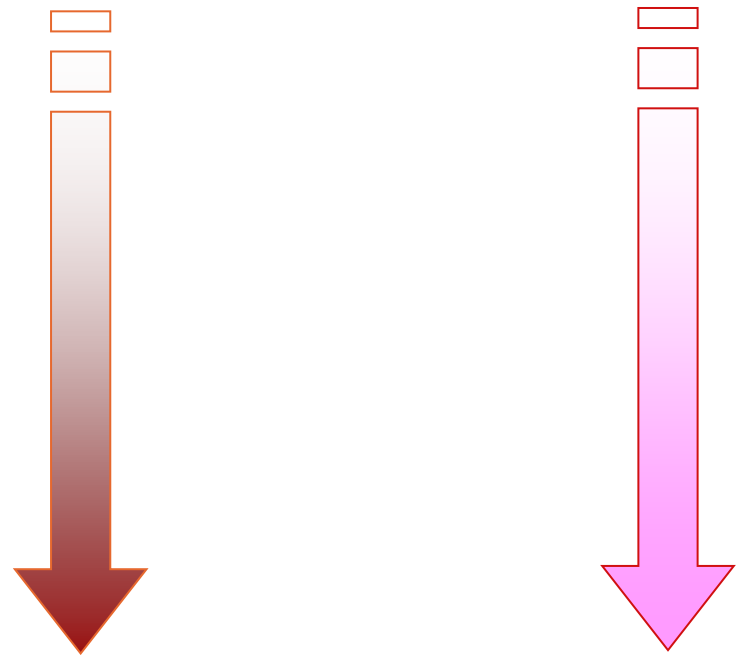


Other Considerations

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

Producibility vs. Total Cost





More design freedom

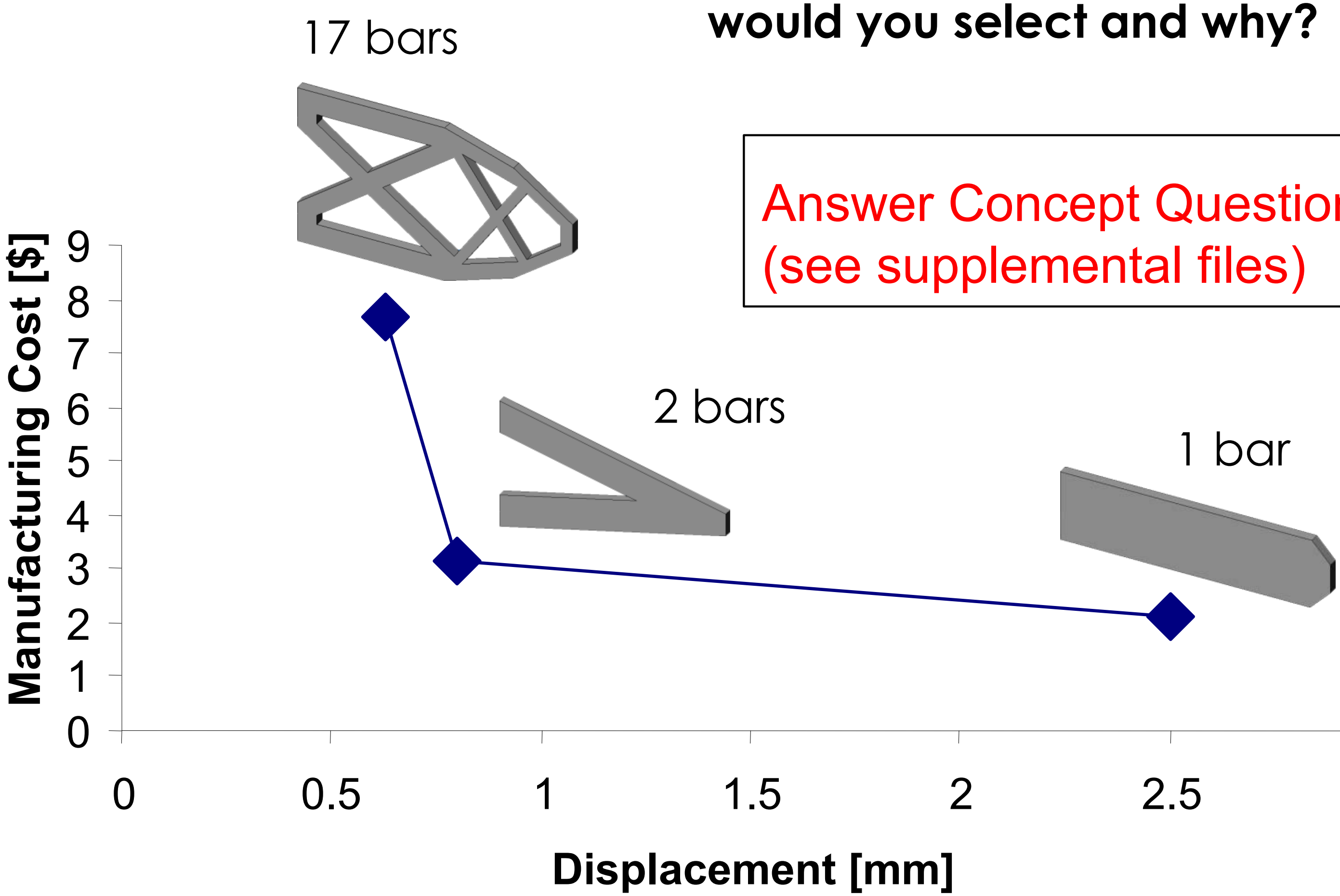
(Better performance)

More complex

(More difficult to optimize)

Concept Question 7

Which of these three designs would you select and why?



Answer Concept Question 7 (see supplemental files)

Outline for today

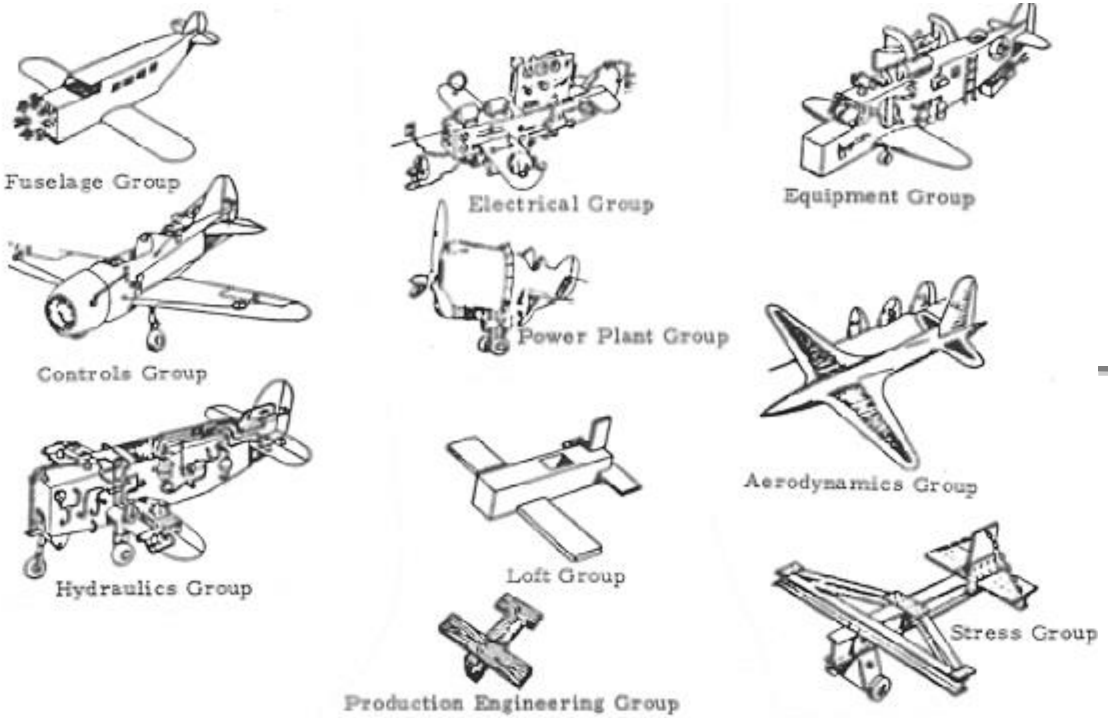
- NASA Design Definition Process
  - Process Overview
- Multidisciplinary Design Optimization
  - What it is and where it fits in…
- Concurrent Design Facilities (CDF)
- Critical Design Review (CDR)

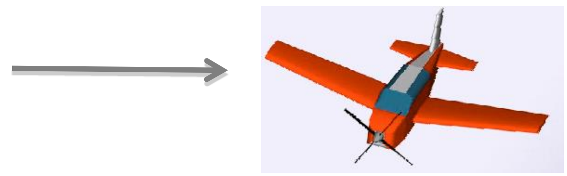
Multidisclinary Design Optimization (MDO) – What it is and where it fits in…

- **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 coupled by physical phenomena and involving many interacting subsystems and parts."

- **Conceptual Components of MDO *(Sobieksi '97)***
  - Mathematical Modeling of a System
  - Design Oriented Analysis
  - Approximation Concepts
  - System Sensitivity Analysis
  - Classical Optimization Procedures
  - Human Interface

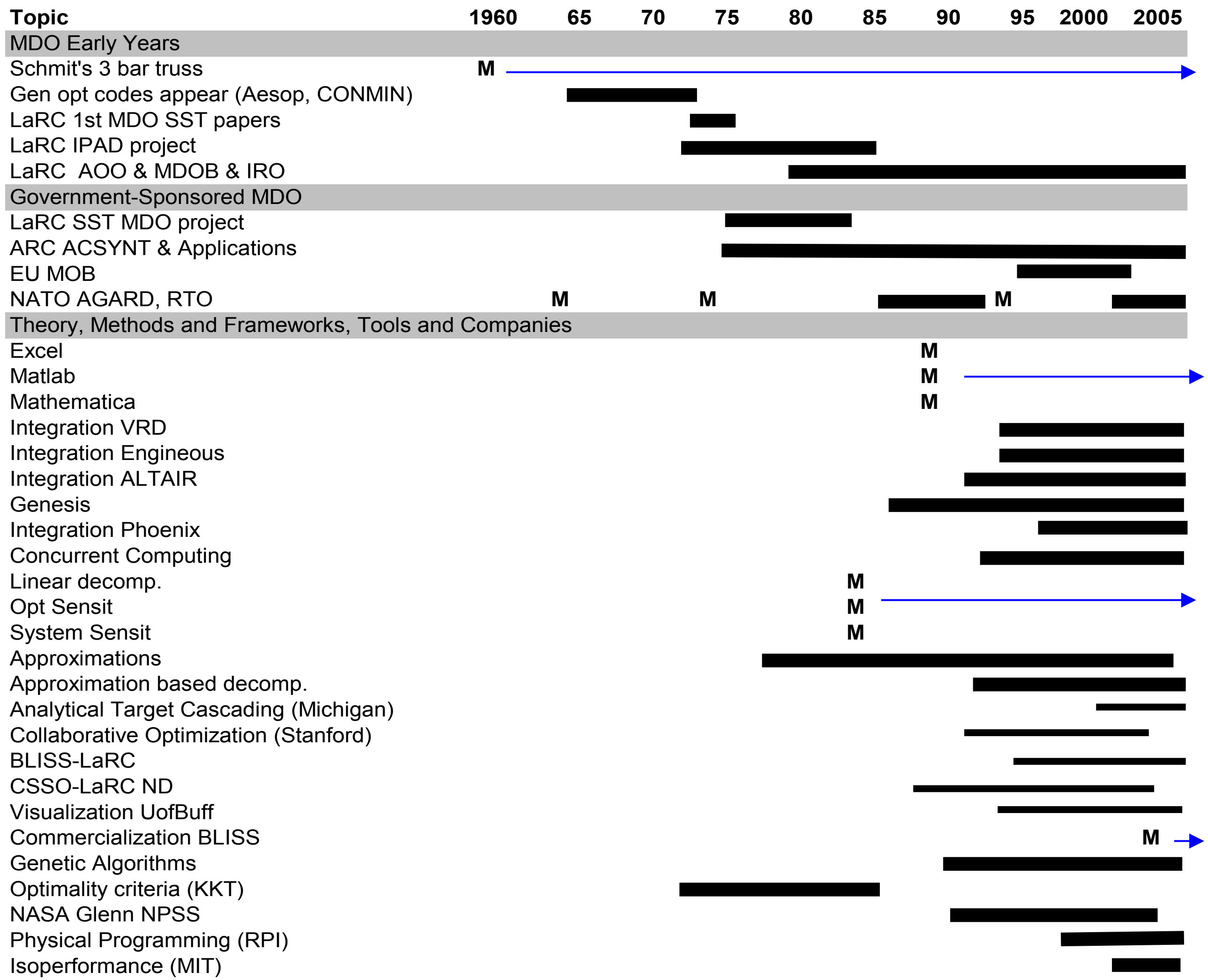
MDO - Motivation





MDO helps us get from this… …to this…

MDO - Roots



MDO roots found in structural optimization

Optimization algrthms in mainstream prgms

More complex decomposition techniques appear

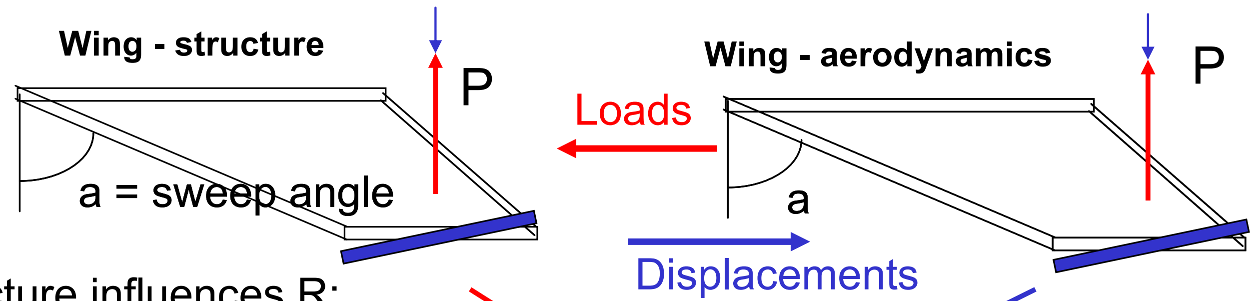
Commercialization of multi-level algorithm

Reading: [6a] Agte J., de Weck O., Sobieszczanski-Sobieski J., Arendsen P., Morris A., Spieck M., "MDO: assessment and direction for advancement - an opinion of one international group", *Structural and Multidisciplinary Optimization*, 40 (1), 17-33, January 2010

MDO - Example

- Simple example of interdependency

Range (R) is the system objective



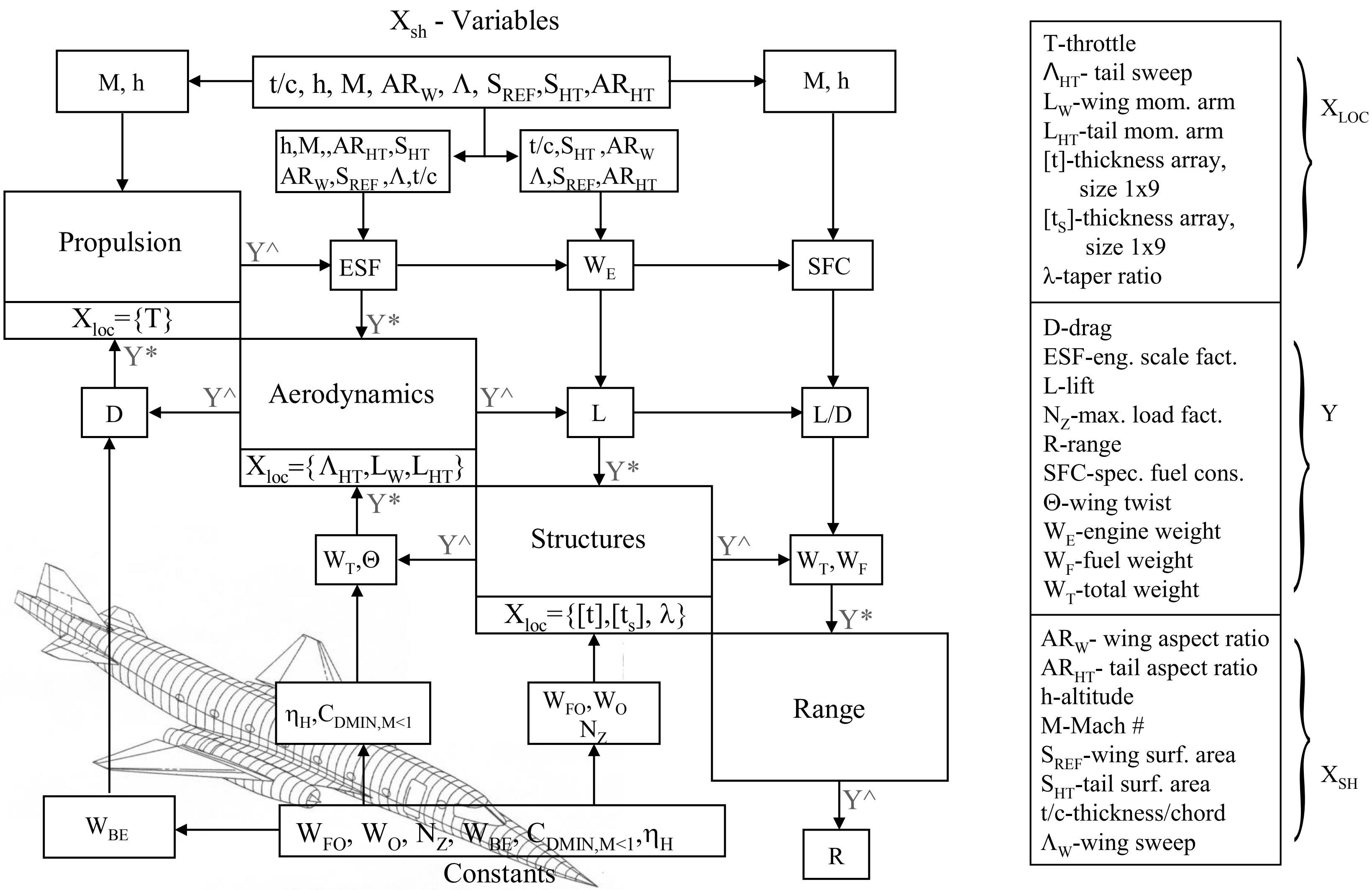
- Structure influences R:
  - directly by weight
  - indirectly by stiffness that affect displacements that affect drag

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?

MDO – Method: Bi-Level Integrated System Synthesis



MDO – Method: Bi-Level Integrated System Synthesis

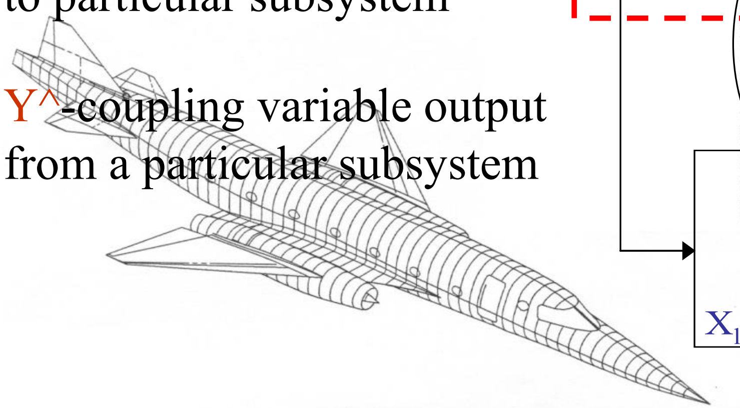
- Formulation of Design System: Supersonic Business Jet Example

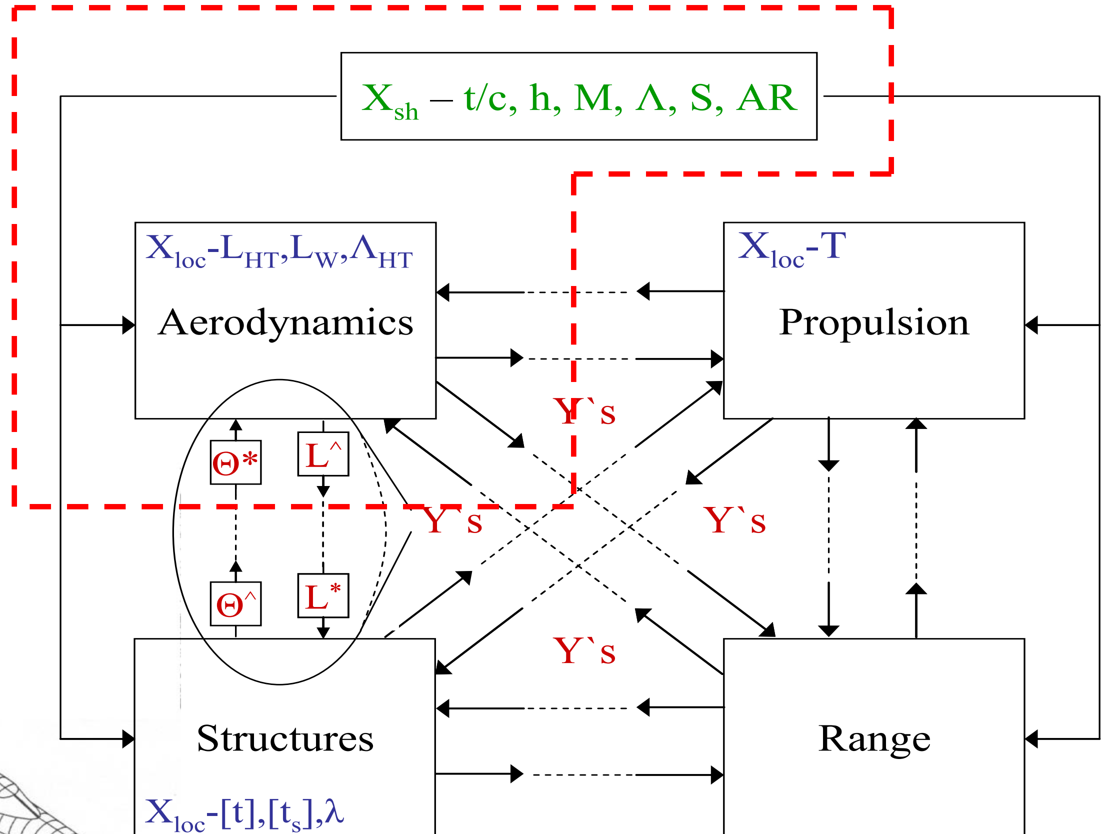
X_{sh}-design variable shared by at least two subsystems

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

Y^*-coupling variable input to particular subsystem

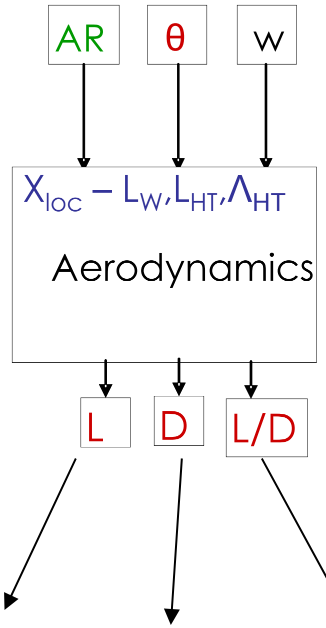
$Y^\wedge$-coupling variable output from a particular subsystem





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

➢ SSOPT Formulation

Given: Q = {[X_{sh}],[Y*],[w]},

minimize: f (w, Y^(X_{loc}, X_{sh}, Y*))

by varying: [X_{loc}].

Satisfy: g(X_{loc}) ≤ 0

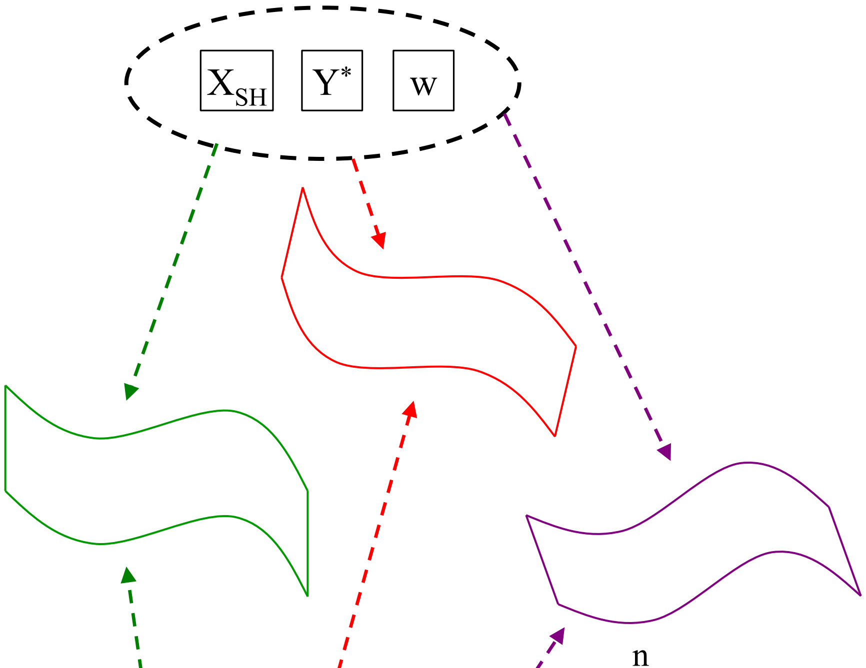
h(X_{loc}) = 0 and

[$X_{loc,LB}$] ≤ [X_{loc}] ≤ [$X_{loc,UB}$],

and retrieve: [X_{loc}] and [Y^] at optimum

MDO – Method: Bi-Level Integrated System Synthesis

- Subsystem Optimization (SSOPT)



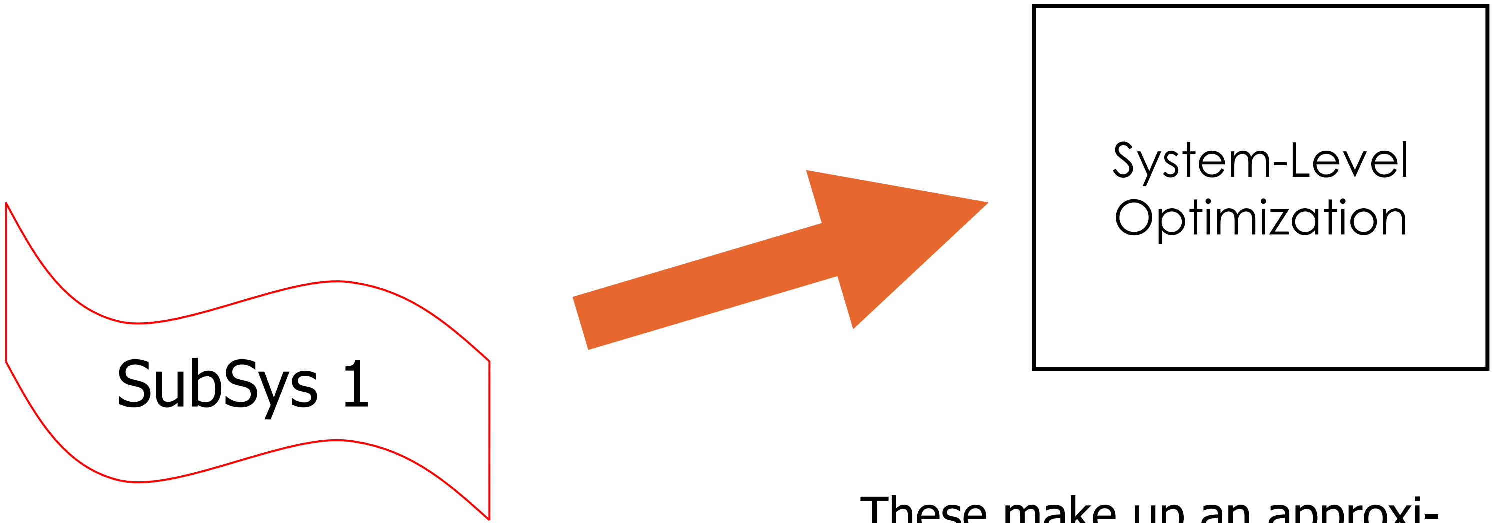
$$f = w_1 \hat{Y}_1 + w_2 \hat{Y}_2 + w_3 \hat{Y}_3 = \sum_{i=1}^{n} w_i \hat{Y}_i$$

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)

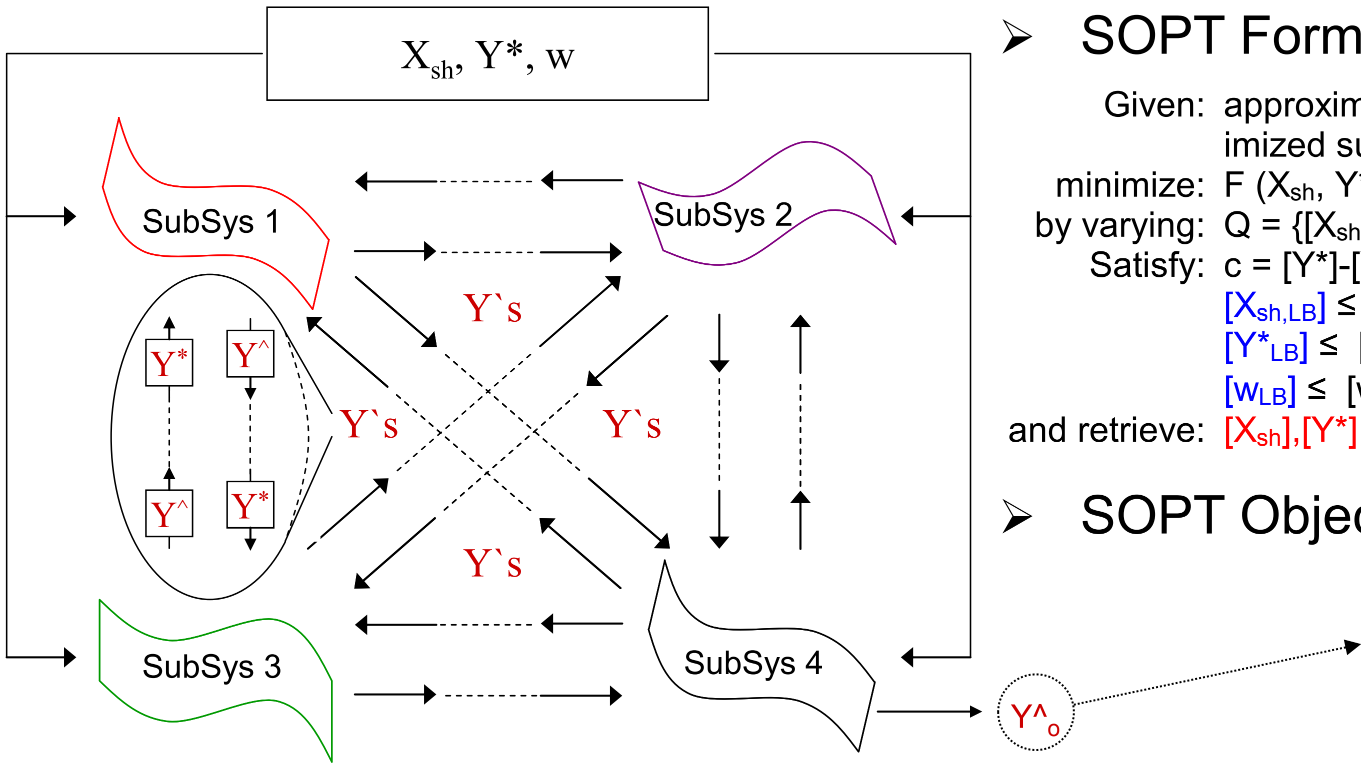


These make up an approxi-mated subsystem…

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

MDO – Method: Bi-Level Integrated System Synthesis

- System Optimization (SOPT)

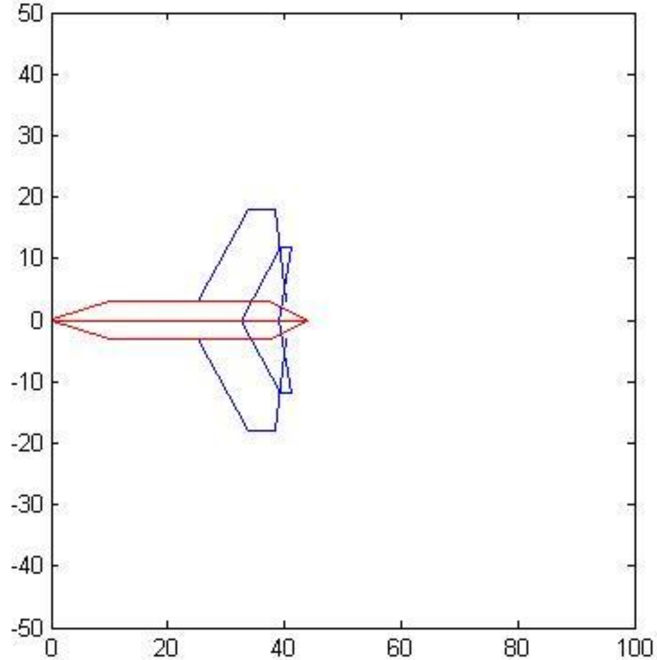


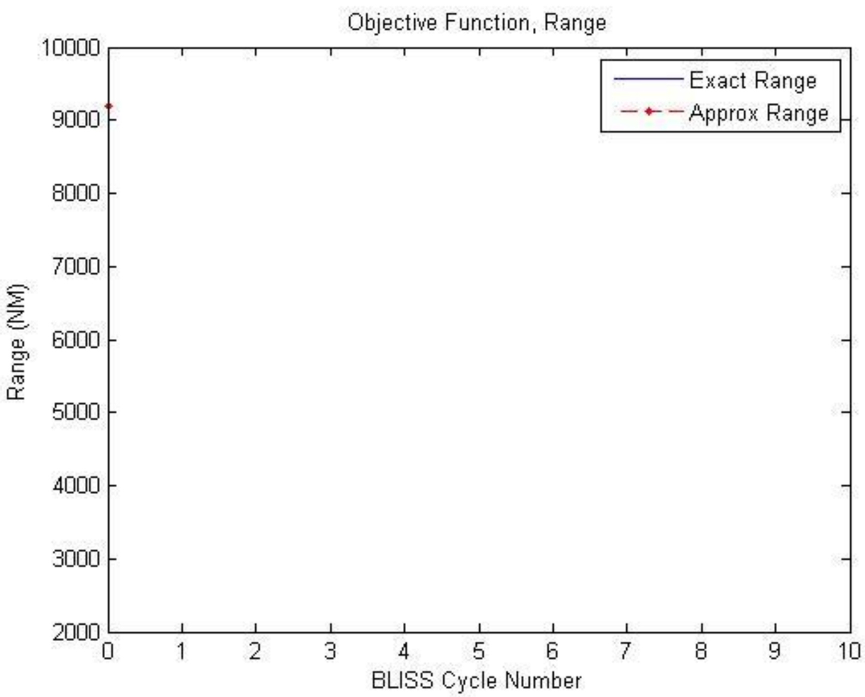
> **SOPT Formulation**

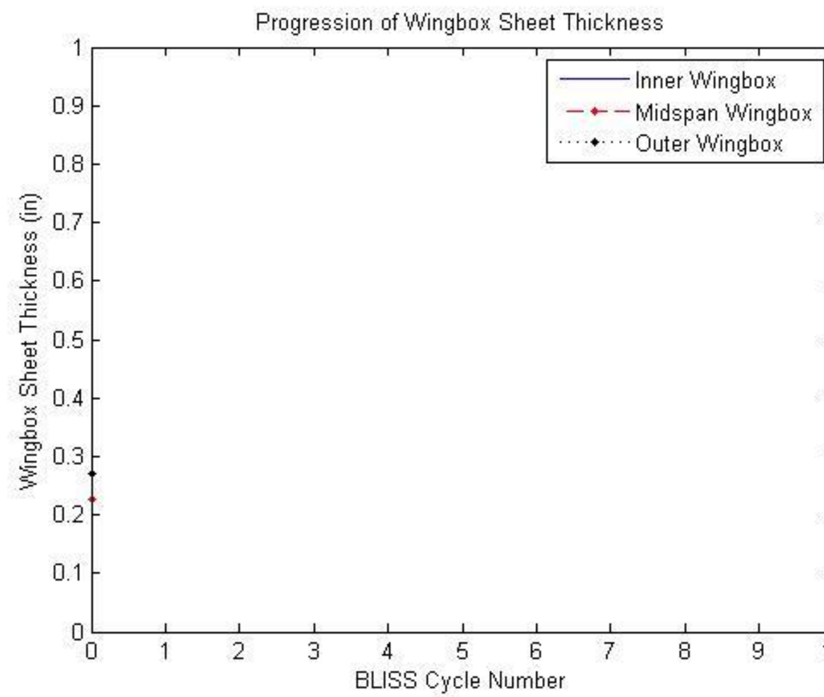
Given: approximation models for optimized subsystem outputs,
minimize: $F(X_{sh}, Y^*, w)$,
by varying: $Q = \{[X_{sh}],[Y^*],[w]\}$.
Satisfy: $c = [Y^*]-[Y^\wedge] = 0$,
$[X_{sh,LB}] \leq [X_{sh}] \leq [X_{sh,UB}]$,
$[Y^*_{LB}] \leq [Y^*] \leq [Y^*_{UB}]$, and
$[w_{LB}] \leq [w] \leq [w_{UB}]$,
and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

> **SOPT Objective Function**

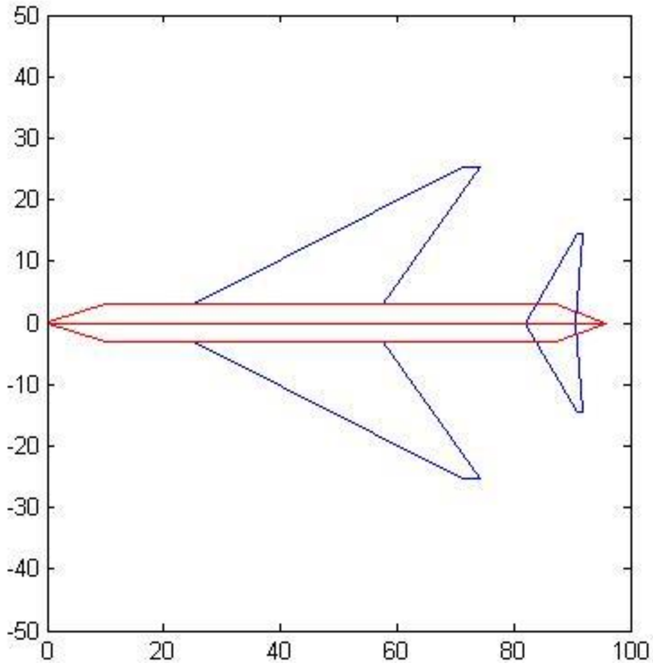
BLISS Cycle # 0

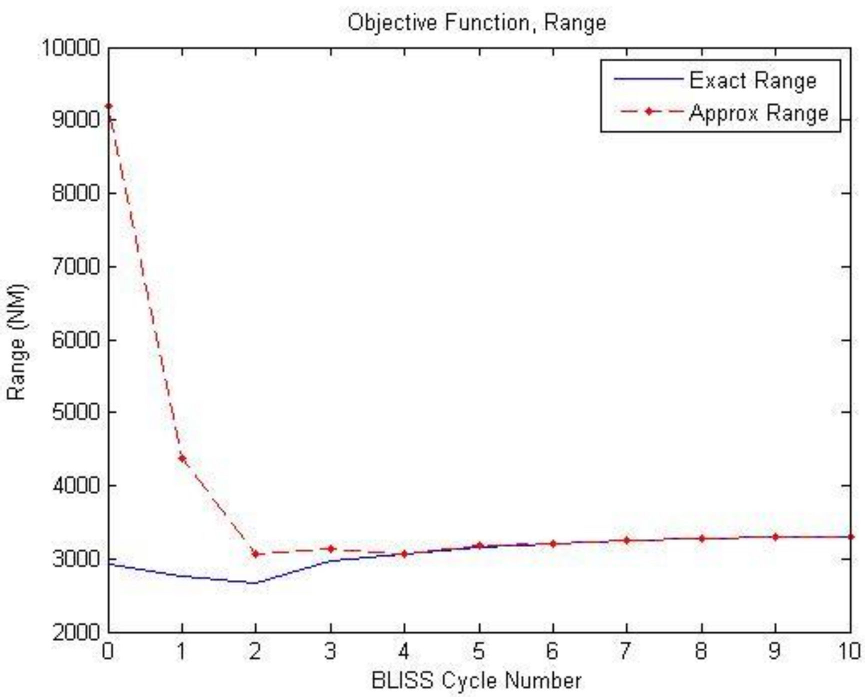


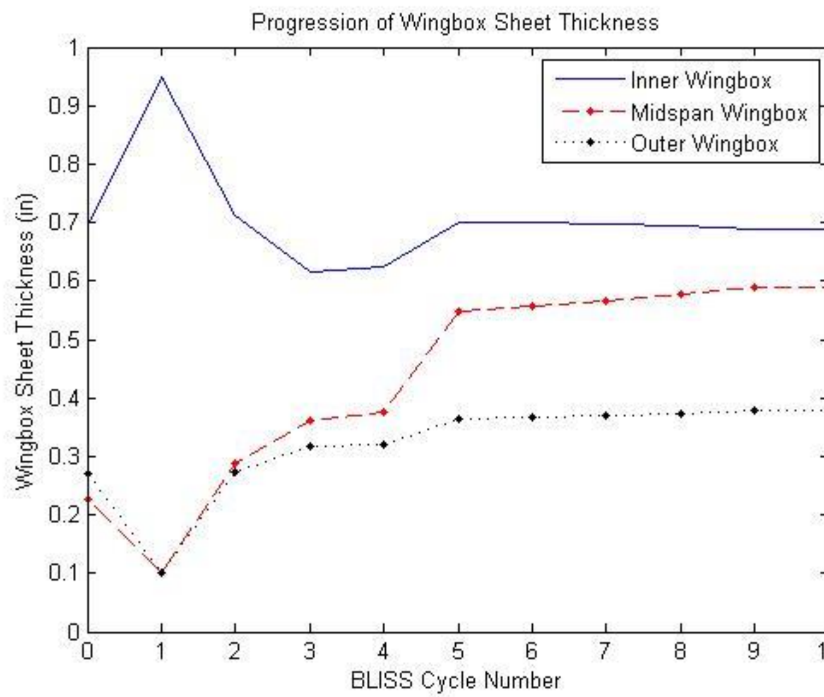




BLISS Cycle # 10

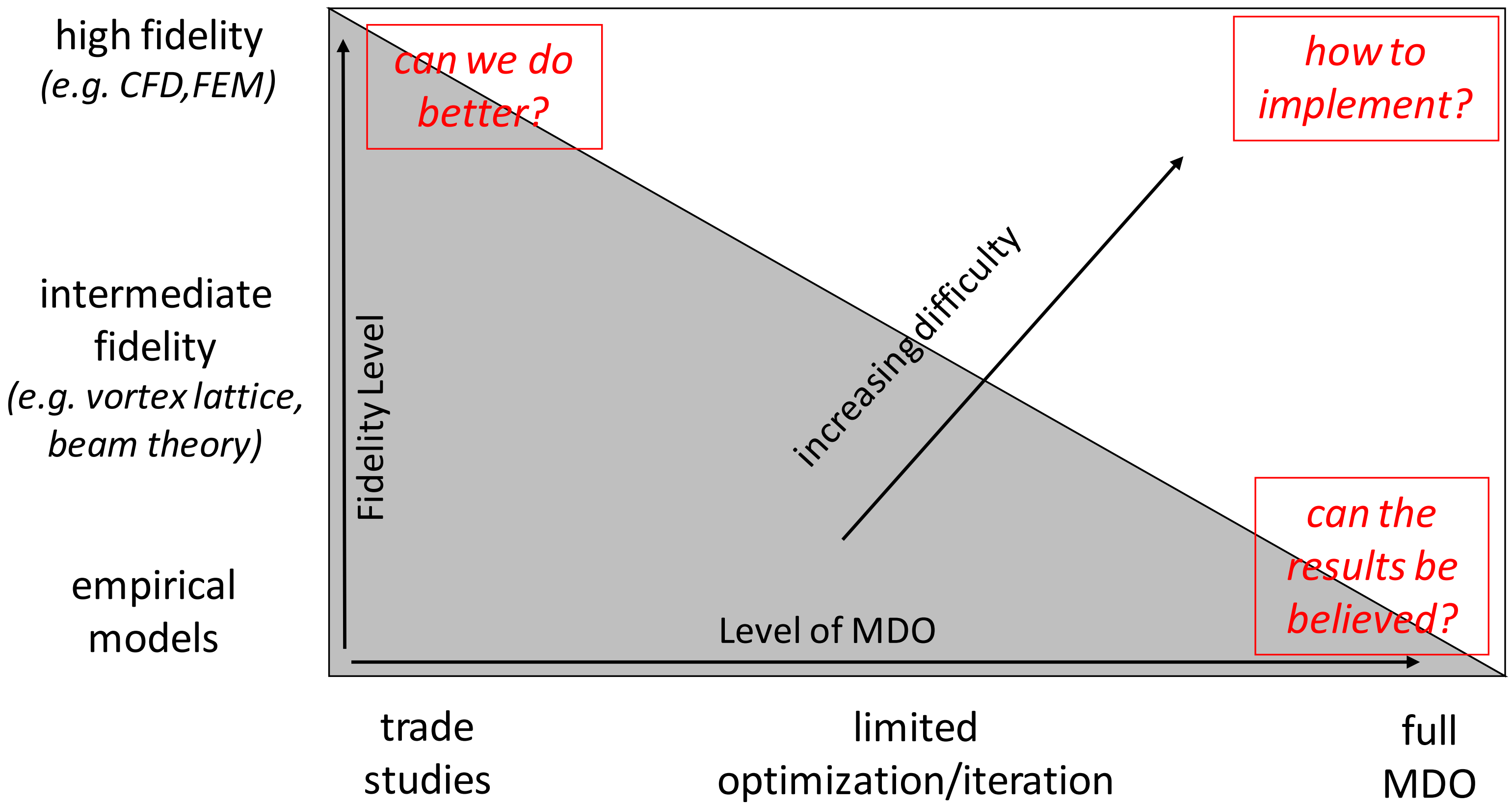






MDO - Challenges

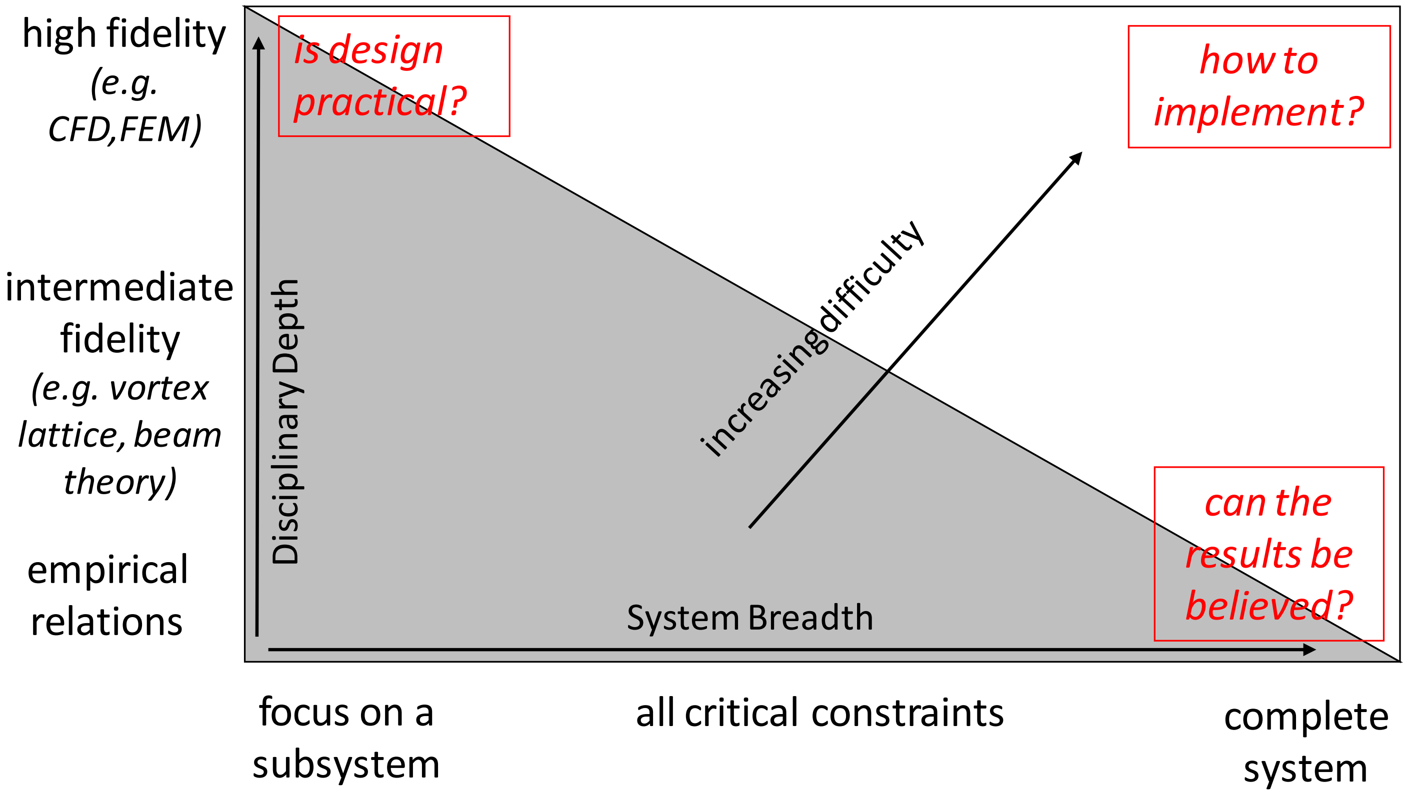
Fidelity vs. Expense



from Giesing, 1998

MDO - Challenges

Breadth vs. Depth



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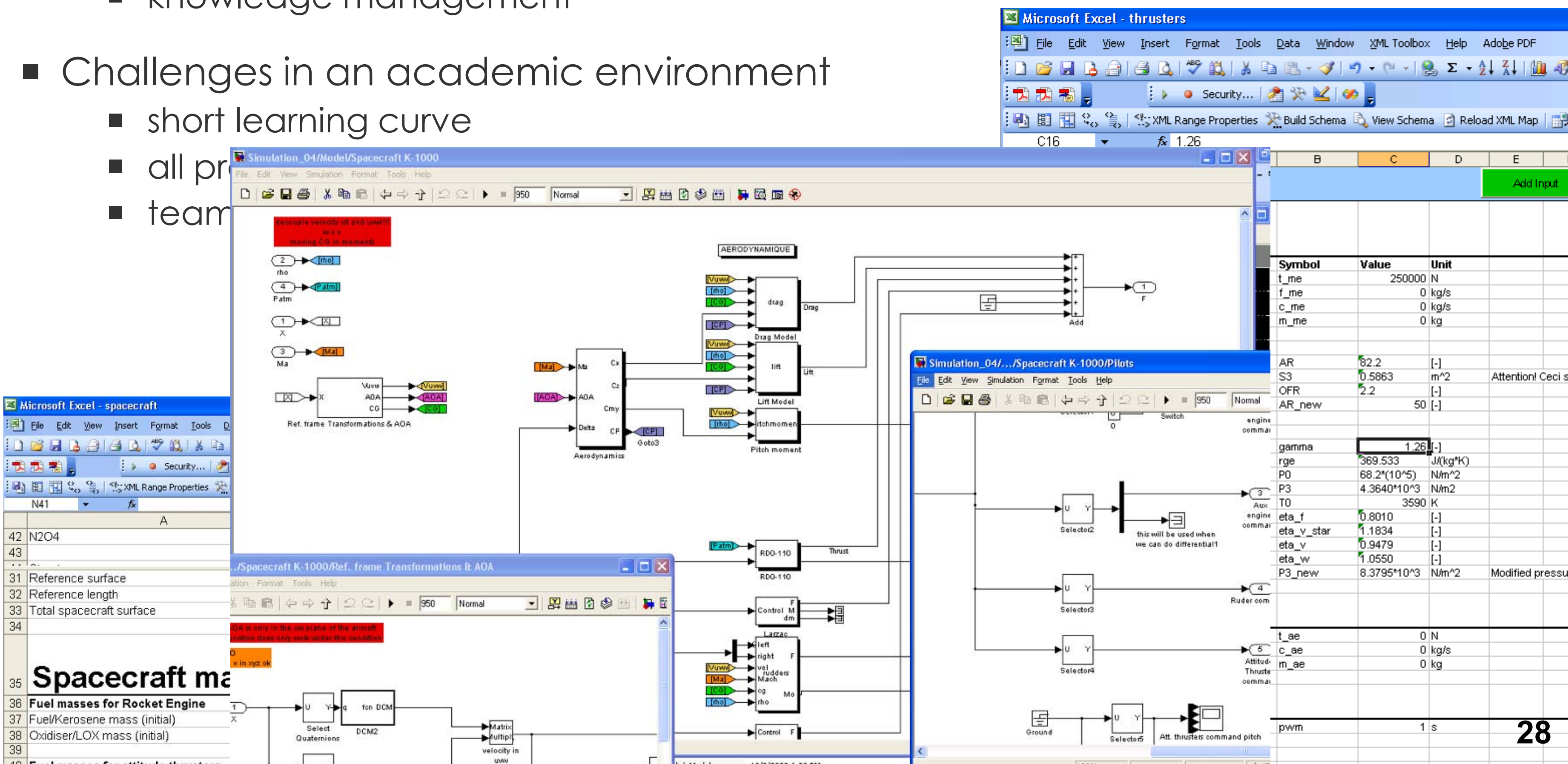
- Critical Design Review (CDR)

Concurrent design approach

Credit:
Dr. A. Ivanov

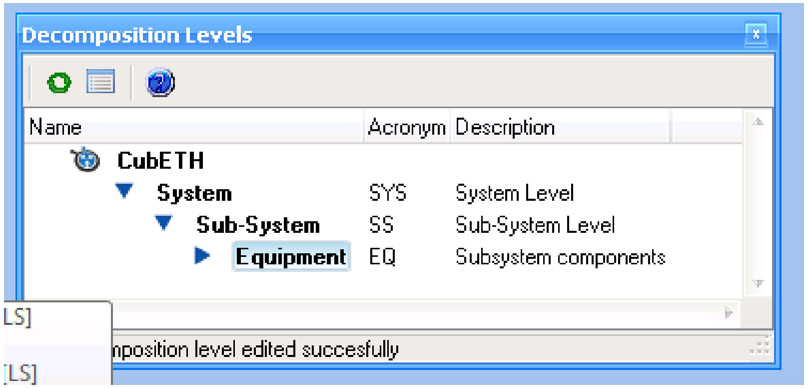
- A **Concurrent design facility (CDF)** is an environment where engineers of different specialties come together to perform a system engineering study for a project. Key elements for a CDF:
  - team
  - process
  - environment (including A/V and software)
  - knowledge management
- Challenges in an academic environment
  - short learning curve
  - all pr
  - team



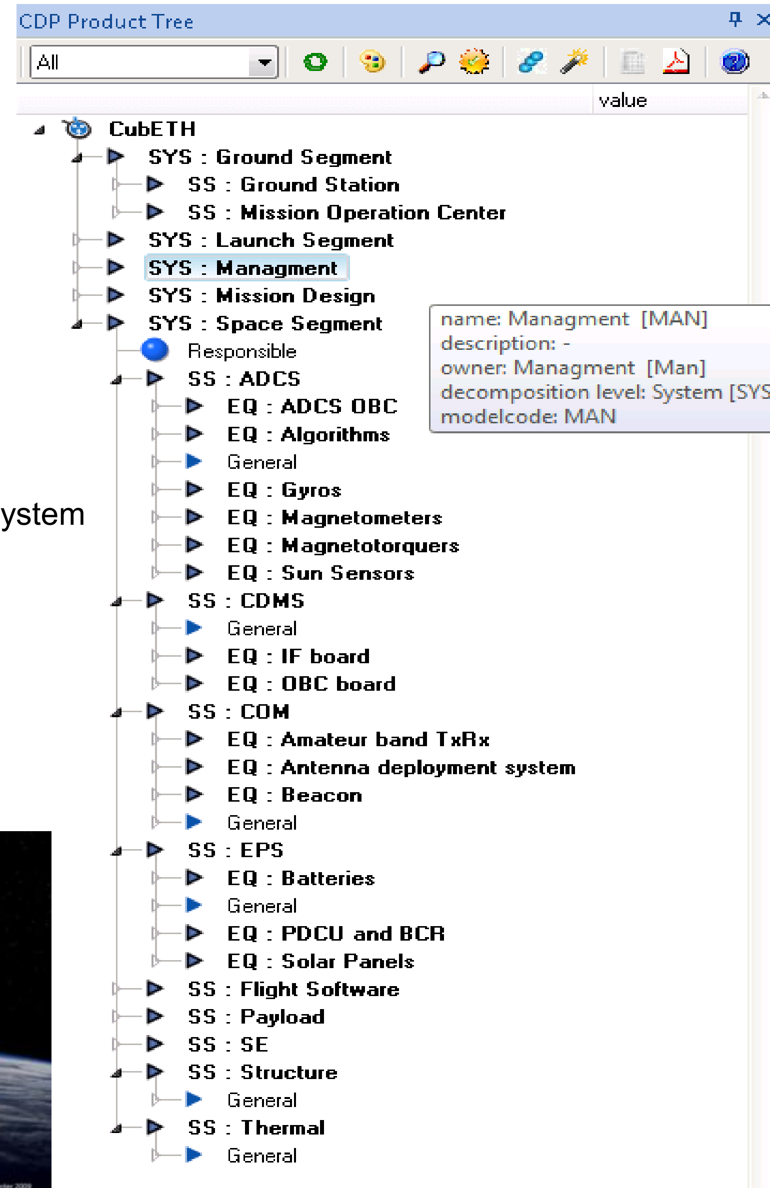
CDF in industrial setting

- **Design centers in Space Agencies**
  - JPL: TeamX
    - studies have shown than cost estimations of TeamX were within 10% of the final mission cost
    - rapid assessment of proposals
  - ESTEC (ESA)
    - all of the future projects at ESA are going through the ESA CDF
    - e.g. CHEOPS
  - Others
    - Most NASA centers, ASI, CNES, commercial applications of the idea (painting, shipbuilding, medical devices)
- **Benefits**
  - improvements on quality for redesigned products
  - very quick turnaround for ideas
  - better cost estimates
  - increased creativity and productivity in a company

Example of Cubesat Design in J-CDS



Step 1. Define decomposition levels

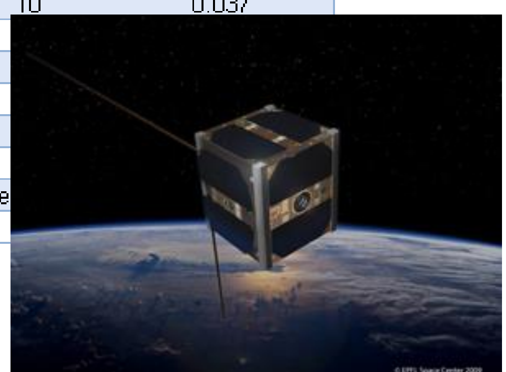


Step 2. Define details of the system

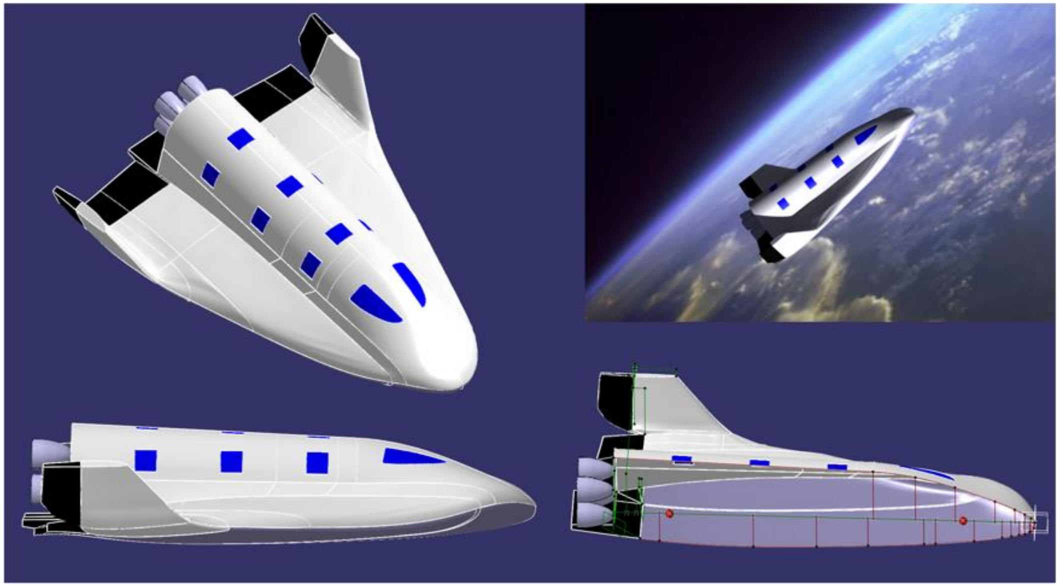
Step 3. Fill in details from databases and models.
Create budgets (mass budget shown)

	A	B	C	D
1	Sum of Valu	shared sublev	Margin [%]	Total with marg
2	Model Code	5		
3	SpS.ADCS	0.133	10	0.146
4	SpS.CDMS	0.034	10	0.037
5	SpS.COM	0.09		
6	SpS.EPS	0.259		
7	SpS.Pay	0.2		
8	SpS.Structure	0.317		
9	Grand Total	**1.033**		
10			Syste	
11				
12				

SwissCube



Design of a suborbital space plane in CDF

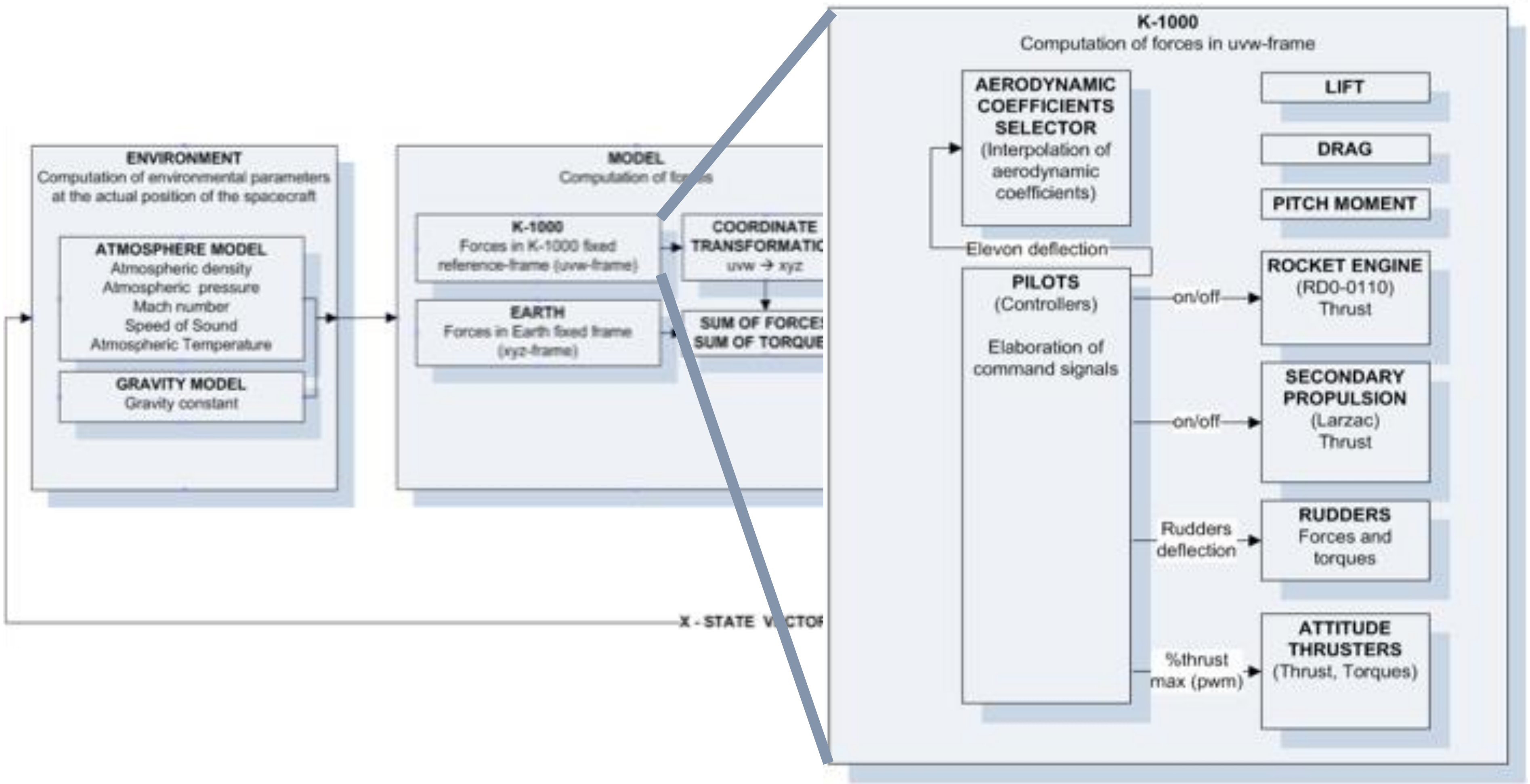


Isometric views of K1000

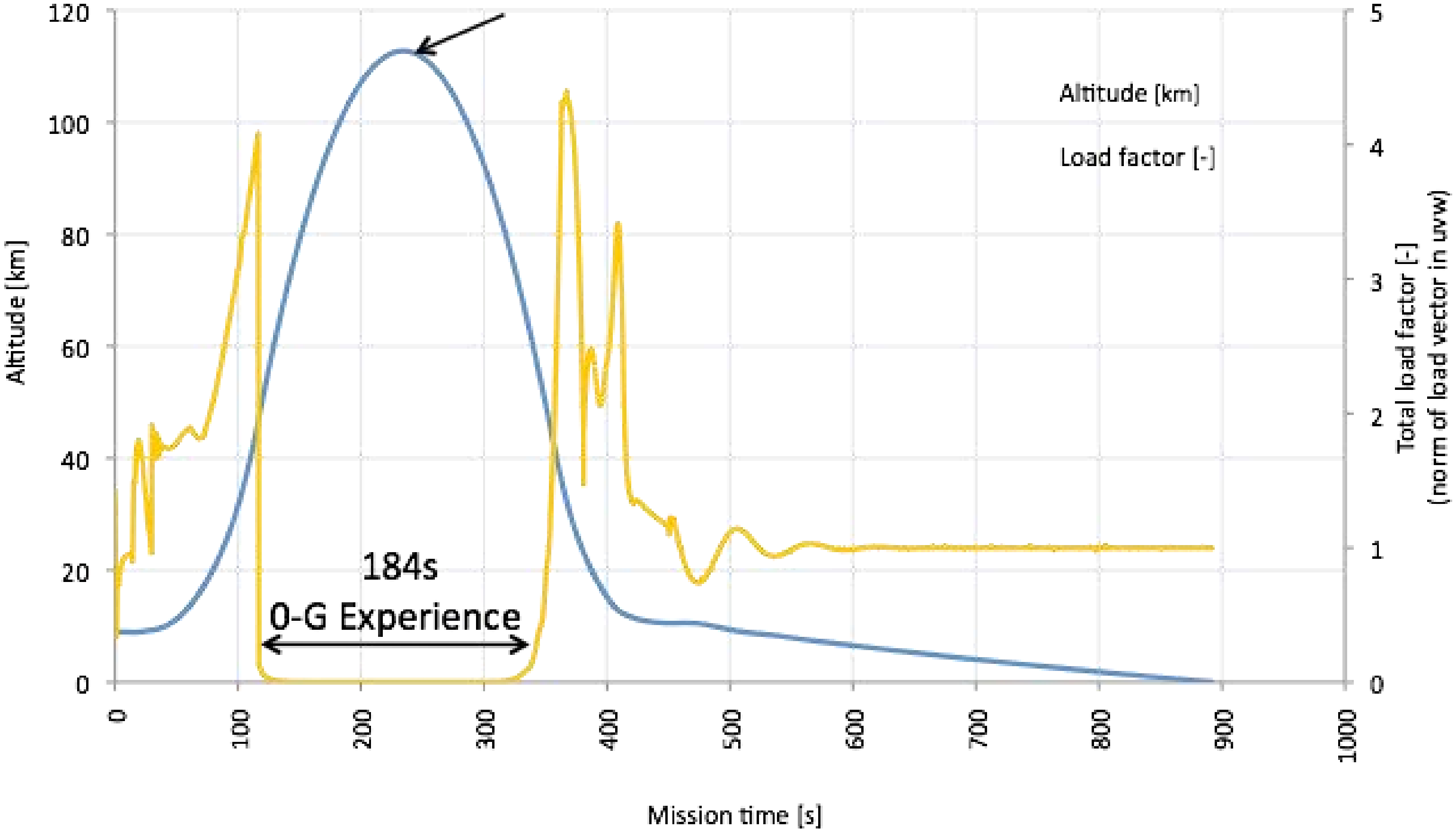
Requirements

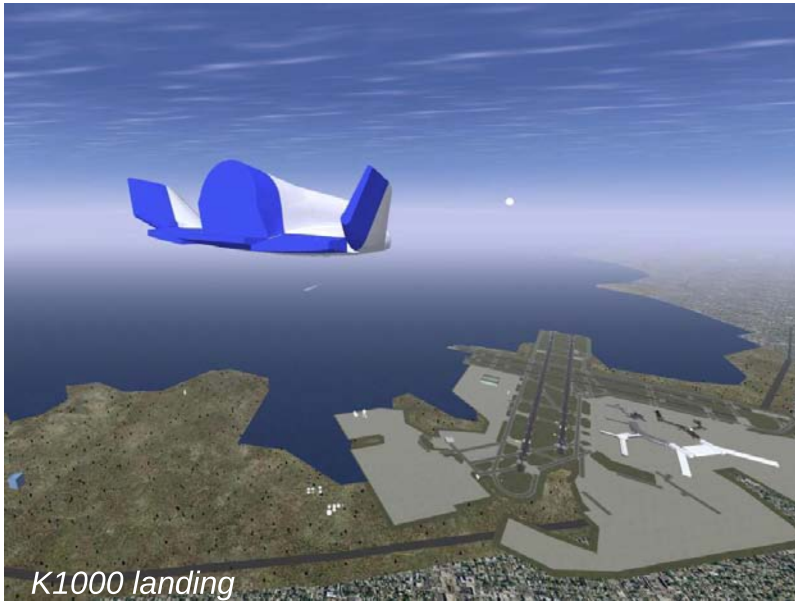
- **Level 1 requirements.**
  - Reach an altitude of at least 100km over sea level
  - Zero G-phase flight phase of several minutes
  - Passenger vehicle carrying 6 people
- **Level 2 requirements**
  - Safety: load limit 6 g
  - Spacecraft shall be controllable at any time
  - Customer experience: view on earth's curvature and atmosphere
  - Environment: The spacecraft's impact on environment should be as small as possible
  - Mass budget: The spacecraft's mass should not exceed 11.6t (with propellants)

CDF Design: K1000

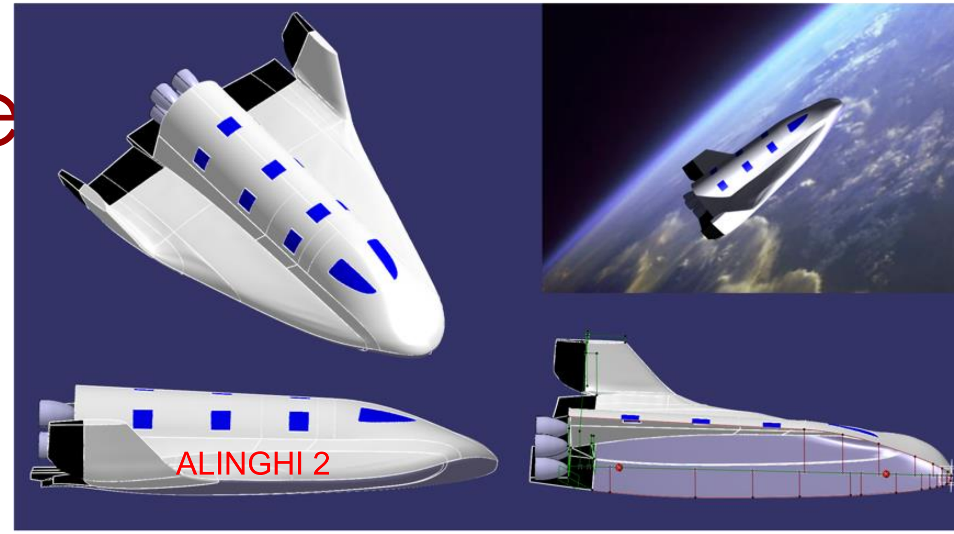


Requirements verification by modeling

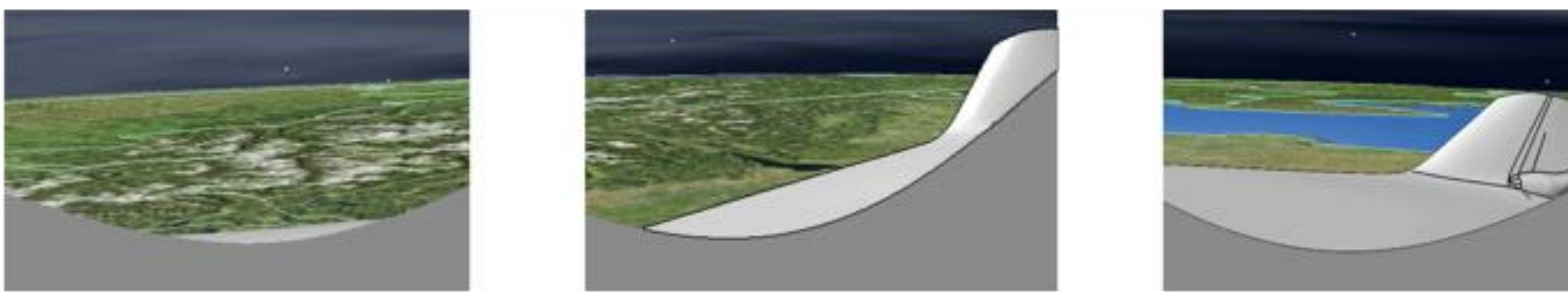




K1000 landing



Isometric views of K1000



View from windows

S3 is it feasible? What are the key challenges?

Partner Exercise (5 min)

- What are your experiences with **Concurrent Design Facilities (CDF)?**
  - For which project or application did you use it?
  - What went well? What did not?
  - What could be improved?
  - **Discuss with your partner.**
  - **Share.**

Lessons learned EPFL CDF

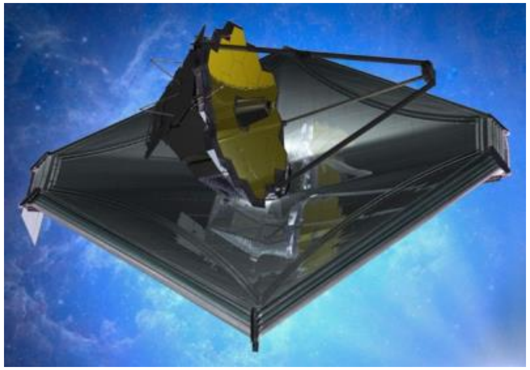
- **The Swiss Space Center CDF operates in a student environment and tied to the university's schedule.**
  - access to a wide body of students and labs who can work on projects in the space center
    - mechanical engineering, robotics, microtechnique, electrical engineering, physics
  - need to adapt to university schedule and cycle
    - very clear formulation of a work package for each student
    - simple schedule and milestones during the semester
  - learning curve
    - emphasis on model development and documentation writing
    - database development
    - encourage teamwork
    - integration into CDF

Lessons learned EPFL CDF (2)

- CDF is a modern analogy of a “smoke-filled room” or “war room”
- Optimal size of the team: 7±2
- Distributed centers
  - a lot of information is lost over telecons
  - videocons are better, but still not ideal, as there is a lot of exchange near “water cooler”
- Staff
  - pulling people from active projects is problematic
  - every chair should be at least 2-3-person deep
- Human interaction is very important
  - humans are still more effective at choosing an optimal scenario and in some cases a scenario that is ‘good enough’ (= isoperformance)
  - multidimensional optimization MDO is an excellent tool on level of subsystems, and also potentially at the system level

Critical Design Review (CDR)

- Critical Design Review (CDR)
  - Main Purpose: Approve the final design and all its details
  - Give Green Light to “cut metal” and manufacture the system
  - Large teams, lots of details …
  - Can last 1+ week for a large complex project



Critical Design Review

The purpose of the CDR is to demonstrate that the maturity of the design is appropriate to support proceeding with full scale fabrication, assembly, integration, and test, and that the technical effort is on track to complete the flight and ground system development and mission operations to meet mission performance requirements within the identified cost and schedule constraints. Approximately 90 percent of engineering drawings are approved and released for fabrication. CDR occurs during the final design phase (Phase C).

For very large projects conduct sub-CDRs for every major element

http://www.techtimes.com/articles/2966/20140126/james-webb-space-telescope-passes-last-major-element-level-critical-design-review-eyes-2018-launch.htm.

CDR Entrance and Success Criteria

Critical Design Review	
Entrance Criteria	**Success Criteria**
1. Successful completion of the PDR and responses made to all PDR RFAs and RIDs, or a timely closure plan exists for those remaining open. 2. A preliminary CDR agenda, success criteria, and charge to the board have been agreed to by the technical team, project manager, and review chair prior to the CDR. 3. CDR technical work products listed below for both hardware and software system elements have been made available to the cognizant participants prior to the review: a. updated baselined documents, as required; b. product build-to specifications for each hardware and software configuration item, along with supporting tradeoff analyses and data; c. fabrication, assembly, integration, and test plans and procedures; d. technical data package (e.g., integrated schematics, spares provisioning list, interface control documents, engineering analyses, and specifications); e. operational limits and constraints; f. technical resource utilization estimates and margins; g. acceptance criteria; h. command and telemetry list; i. verification plan (including requirements and specifications); j. validation plan; k. launch site operations plan; l. checkout and activation plan; m. disposal plan (including decommissioning or termination); n. updated technology development maturity assessment plan; o. updated risk assessment and mitigation; p. update reliability analyses and assessments; q. updated cost and schedule data; r. updated logistics documentation; s. software design document(s) (including interface design documents); t. updated LLIL; u. subsystem-level and preliminary operations safety analyses; v. system and subsystem certification plans and requirements (as needed); and w. system safety analysis with associated verifications.	1. The detailed design is expected to meet the requirements with adequate margins at an acceptable level of risk. 2. Interface control documents are appropriately matured to proceed with fabrication, assembly, integration, and test, and plans are in place to manage any open items. 3. High confidence exists in the product baseline, and adequate documentation exists or will exist in a timely manner to allow proceeding with fabrication, assembly, integration, and test. 4. The product verification and product validation requirements and plans are complete. 5. The testing approach is comprehensive, and the planning for system assembly, integration, test, and launch site and mission operations is sufficient to progress into the next phase. 6. Adequate technical and programmatic margins and resources exist to complete the development within budget, schedule, and risk constraints. 7. Risks to mission success are understood and credibly assessed, and plans and resources exist to effectively manage them. 8. SMA (e.g., safety, reliability, maintainability, quality, and EEE parts) have been adequately addressed in system and operational designs, and any applicable SMA plan products (e.g., PRA, system safety analysis, and failure modes and effects analysis) have been approved.

NASA SE Handbook (2007) p. 178

Summary Lecture 6

- **Detailed Design Phase** is very important
  - Take the PDR-level design and define all the details to full maturity
  - Create design documents and models:
    - Detailed Bill of Materials (BOM)
    - All Computer-Aided-Design (CAD) files
    - Software / Control systems Definition
    - User Interface
- Multidisciplinary Design Optimization (MDO)
  - Optimize at the system or subsystem level
  - Tradeoffs between disciplines and objectives
- Concurrent Design Facilities (CDF)
  - Standard practice in advanced aerospace and product design companies
- **CDR is the last gate before "cutting metal"**