Systems Design and System Architecture

Establishing a Common Language and Set of Methods for Systems Design and Architecture

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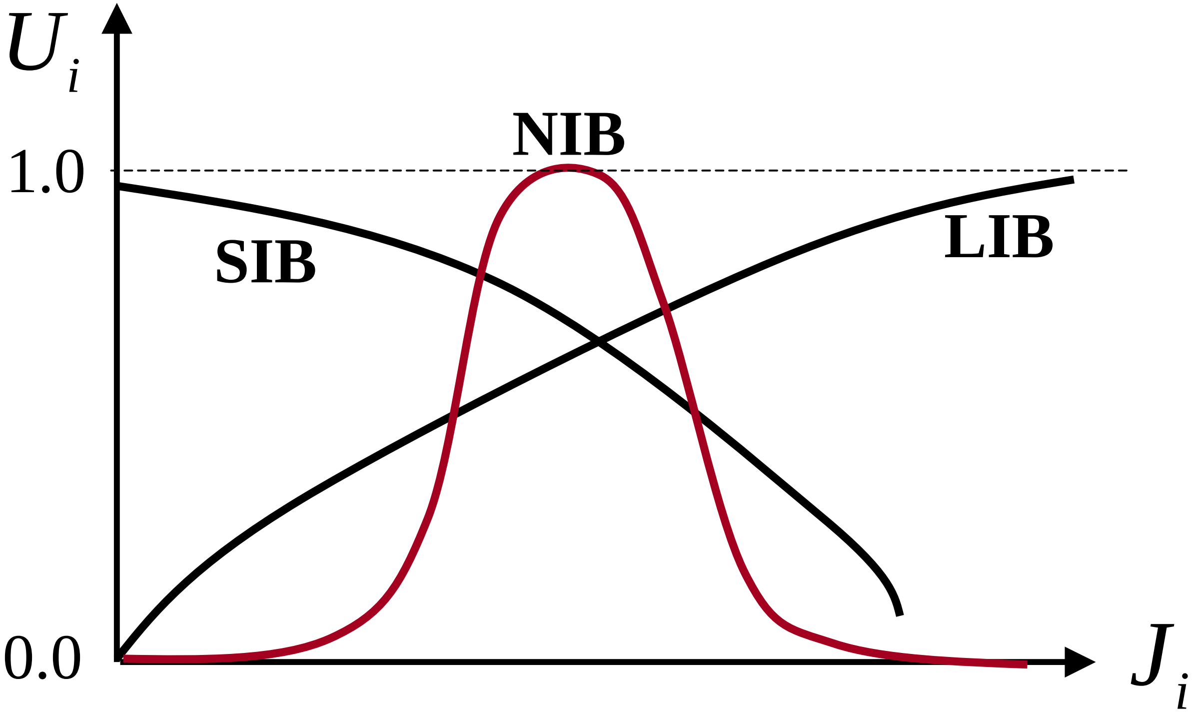
Wake-Up Quote

“The experience of the 1960’s has shown that for military aircraft the cost of the final increment of performance usually is excessive in terms of other characteristics and that the overall system must be optimized, not just performance.”

AIAA Technical Committee on Multidisciplinary Design Optimization (MDO)
White Paper on Current State of the Art
January 15, 1991

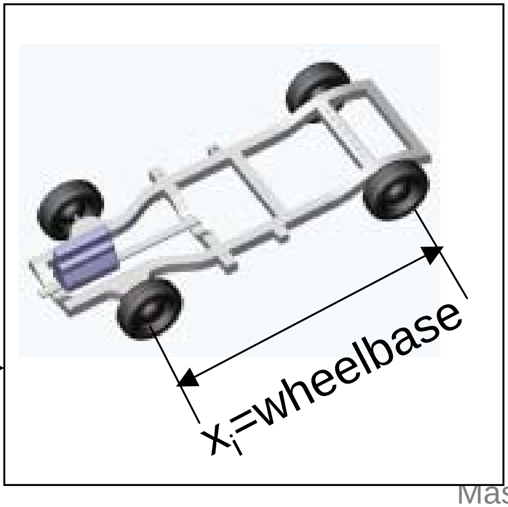
Utility of System Attributes



Example:

Vehicle
Design

x



Vehicle
Objectives

J

NIB: Range
SIB: Fuel Consumption
LIP: Crashworthiness

Fundamental Dilemma

System Architects

System Architects don’t know how to quantify the goodness of their architectures or concepts

No feedback

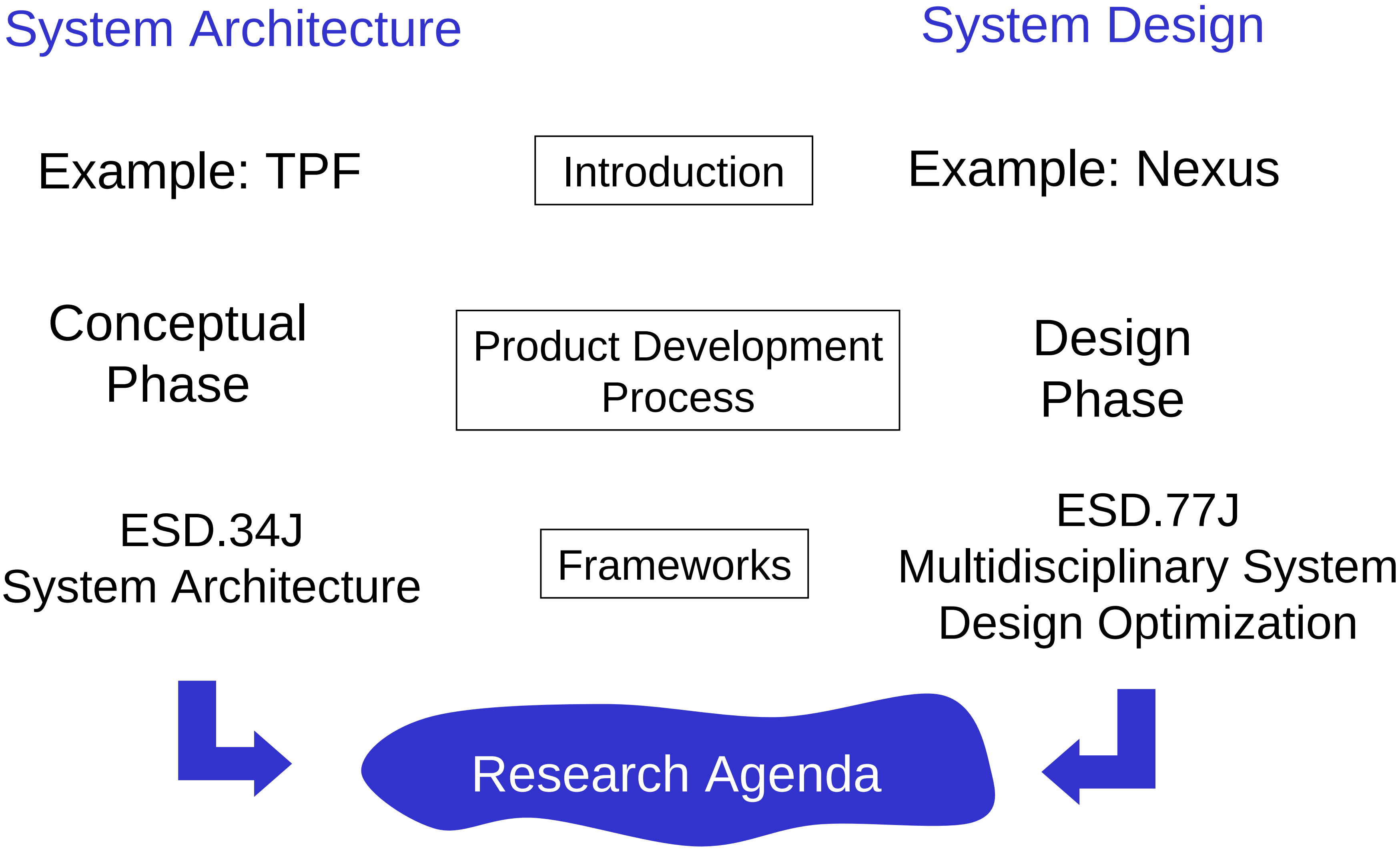
Barrier

(Methodology, Time Pressure, Uncertainty)

System Designers spend a lot of time designing or optimizing bad architectures or flawed concepts

System Designers

Outline



System Architecture

System Design

Example: TPF

Introduction

Example: Nexus

Conceptual Phase

Product Development Process

Design Phase

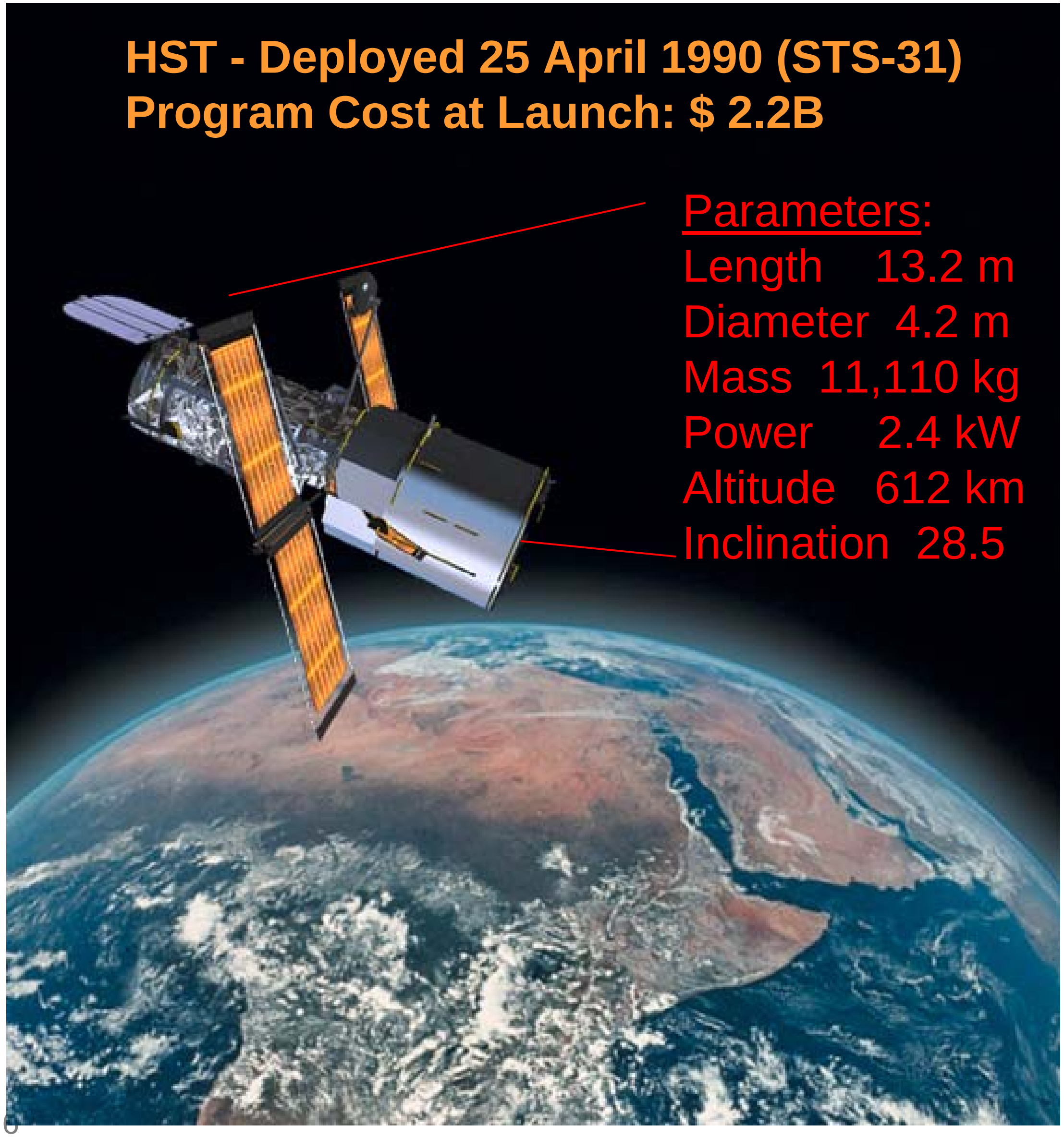
ESD.34J
System Architecture

Frameworks

ESD.77J
Multidisciplinary System Design Optimization

Research Agenda

My Engineering Systems World



HST - Deployed 25 April 1990 (STS-31)
Program Cost at Launch: $ 2.2B

Parameters:

Length	13.2 m
Diameter	4.2 m
Mass	11,110 kg
Power	2.4 kW
Altitude	612 km
Inclination	28.5

Space-Based Observatory
Multipurpose UV/Visual/IR
Imaging and Spectroscopy

Specifications:

Aperture D:	2.4 m
Wavelengths λ:	0.11-2.6 μm
Focal Ratio:	f/24
Resolution:	0.044” at 0.5 μm
Encircled Energy:	0.86 at 0.1”
Pointing Stability:	0.007” RMS

Limitations:
- MIR Observation λ>3 mm
- Angular Resolution
- Zodi/Albedo in LEO

➡ Need a new generation of space observatories

Architecting versus System Design

Architecture: “Art and Science of Building”*

Typical Decision Variables:

“discrete”

- Number of Satellites/Apertures , Constellation Type
- Operating Altitude (LEO, GEO, MEO, L2, Heliocentric)
- Aperture geometry (monolith, segmented, sparse)
- Modular vs Integral
- Structurally Connected vs. Formation Flying

Design: “Drawing or outline from which something may be made”*

Typical Decision Variables:

“continuous”

- Control system design (ACS, Optical Control)
- Structural design (truss, shells, Inflatables, E, I, G ...)
- Optical parameters (Aperture size D, focal ratio F/#)
- Thermal design (radiator size, cryocooler capacity)
- Detectors (CCD format, quantum efficiency,…)

*[Oxford Dictionary of Current English, Oxford University Press, 1984]

TPF Architecture Exploration

Inputs (Design Vector)

- Heliocentric Orbital Altitude
- Number of Apertures
- Interferometer Type
- Aperture Size

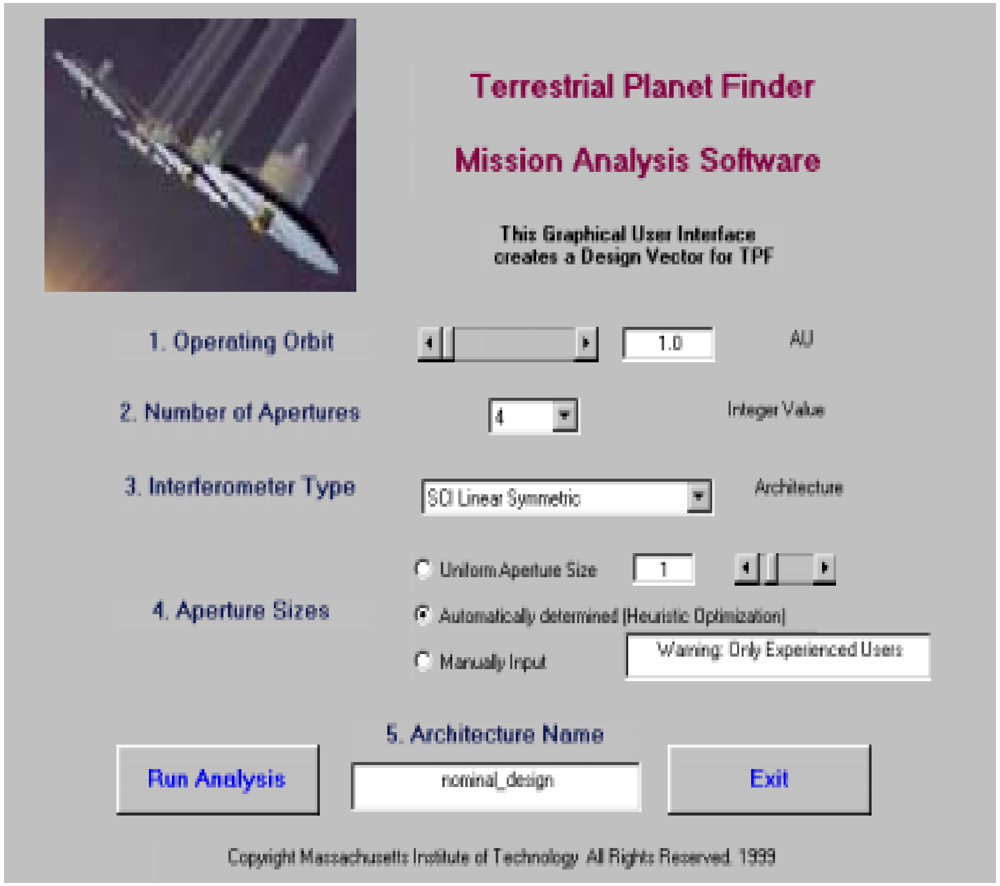
TPF Mission Analysis Software

Outputs (Key Metrics)

- Total Lifecycle Cost
- Total Mass
- Number of Images
- Cost per Image

Architecture Trade Space:

Heliocentric Altitude: 1.0,1.5,2.0,2.5,3.0,3.5,4.0,4.5,5.0,5.5 [AU]
Number of Collector Apertures: 4,6,8,10,12
Interferometer Type: SCI-1D, SCI-2D, SSI-1D, SSI-2D
Aperture Size (Diameter): 1,2,3,4 [m]



Terrestrial Planet Finder

Mission Analysis Software

This Graphical User Interface creates a Design Vector for TPF

1. Operating Orbit: 1.0 AU
2. Number of Apertures: 4 (Integer Value)
3. Interferometer Type: SCI Linear Symmetric (Architecture)
4. Aperture Sizes:
   - ○ Uniform Aperture Size: 1
   - ● Automatically determined (Heuristic Optimization)
   - ○ Manually Input: Warning: Only Experienced Users
5. Architecture Name: nominal_design

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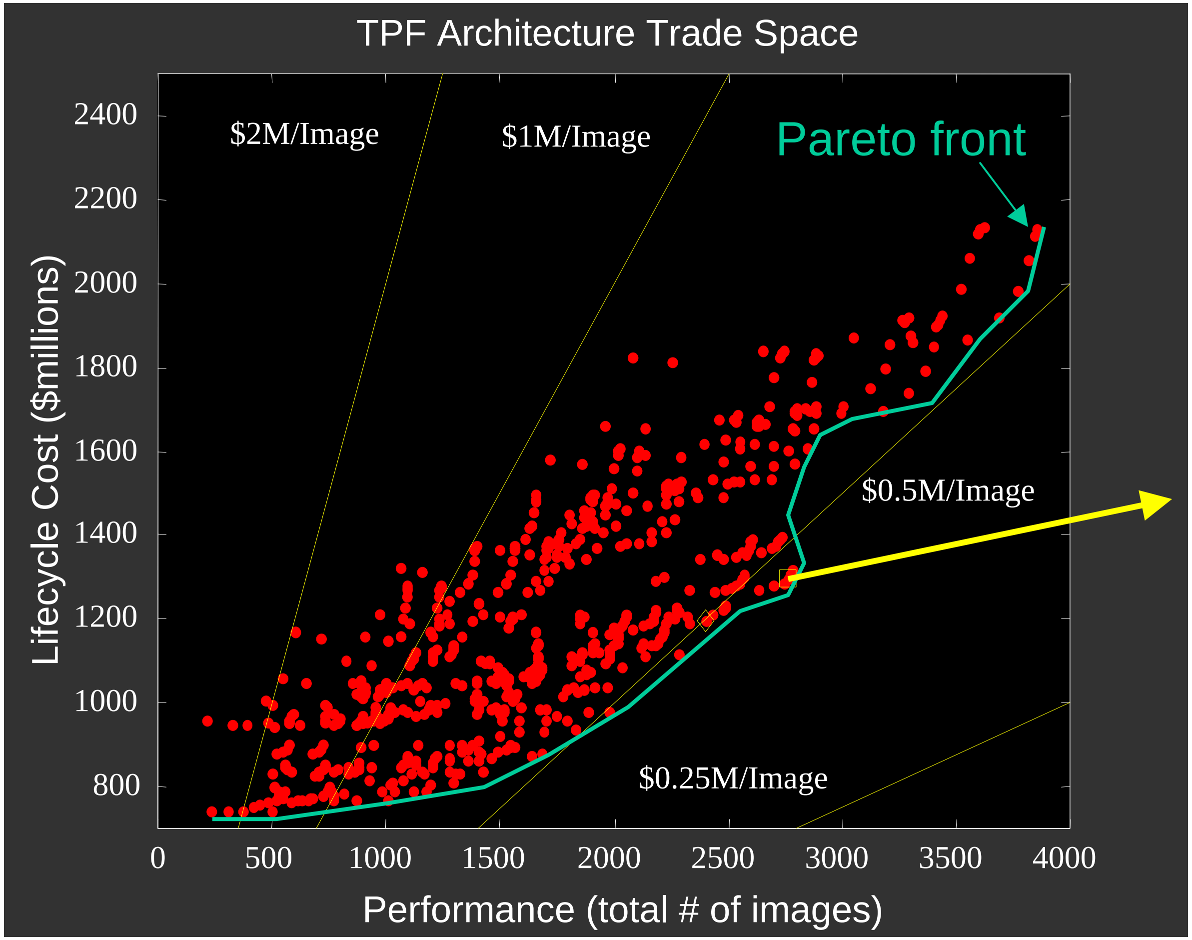
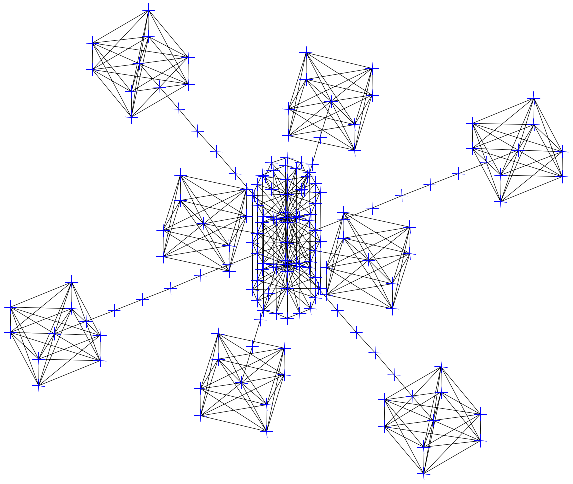
Architectural Trade Space

Exhaustive Trade Space Evaluation

Factorial Trade Space has a total of 640 solutions

Which architecture gives the best cost/function ?





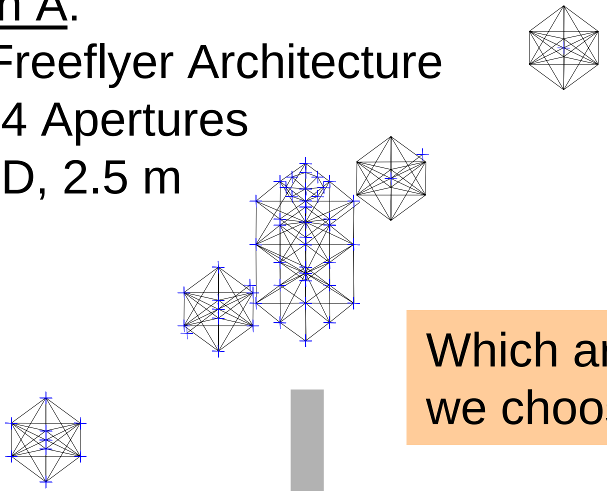
Optimal Solution:
Orbital Altitude = 4 AU
Number of Apertures = 8
Interferometer = SCI-2D
Aperture Size = 4m
CPI = 469.6 k$/image

Figure Courtesy: Cyrus Jilla

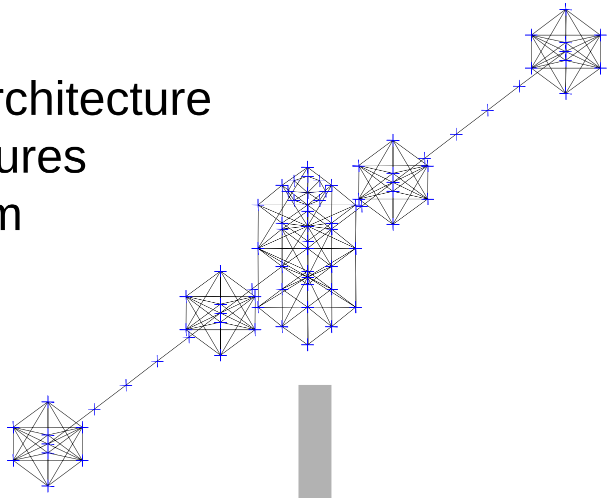
Caution: Sensitivity Analysis

Caution: Small changes in assumption at the design level can have very LARGE consequences at the architecture level and influence decisions.

Option A:
TPF Freeflyer Architecture
1AU, 4 Apertures
SSI-1D, 2.5 m



Option B:
TPF Truss Architecture
1AU, 4 Apertures
SCI-1D, 2.0 m



Which architecture do we choose ? Lowest CPI !

Case 1: 933 images, $1006.6M, **1078 k$ CPI**
Case 2: 919 images, $1006.6M, **1095 k$ CPI**

Case 1: 769 images, $769.5M, **1000 k$ CPI**
Case 2: 633 images, $769.5M, **1215 k$ CPI**

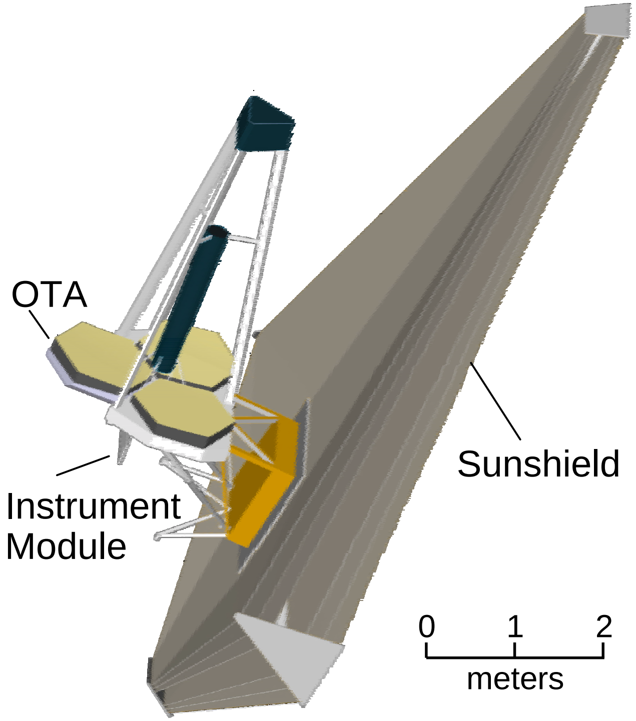
Case 1: Reaction wheel imbalance Us=0.716 gcm , Case 2: Us=7.16 gcm

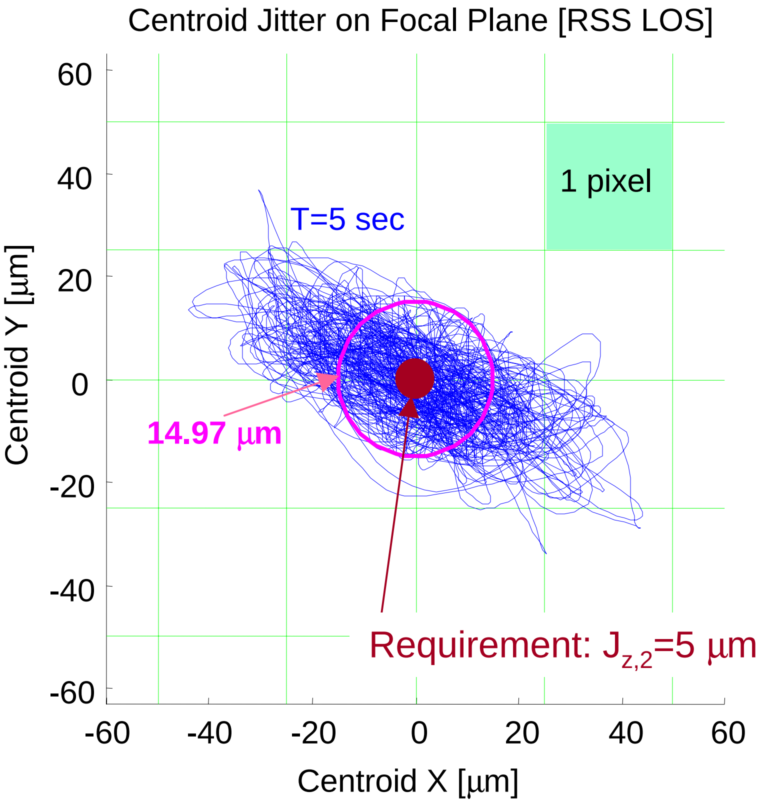
Conclusion:

System Architecting and System Design are intimately connected and cannot be separated for high-performance systems.

Example 1a: Spacecraft Design

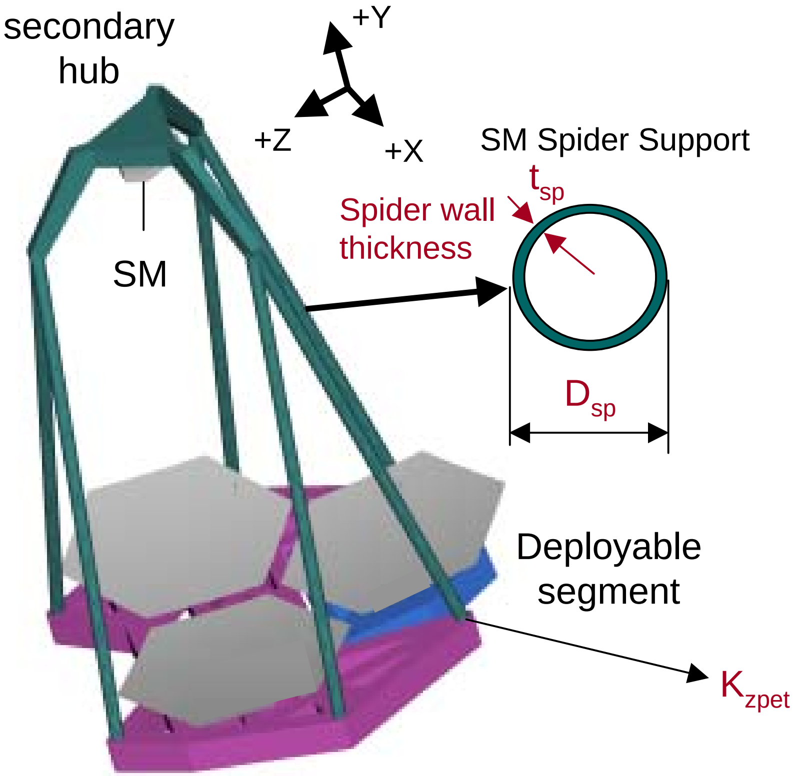
NASA Nexus Spacecraft Concept



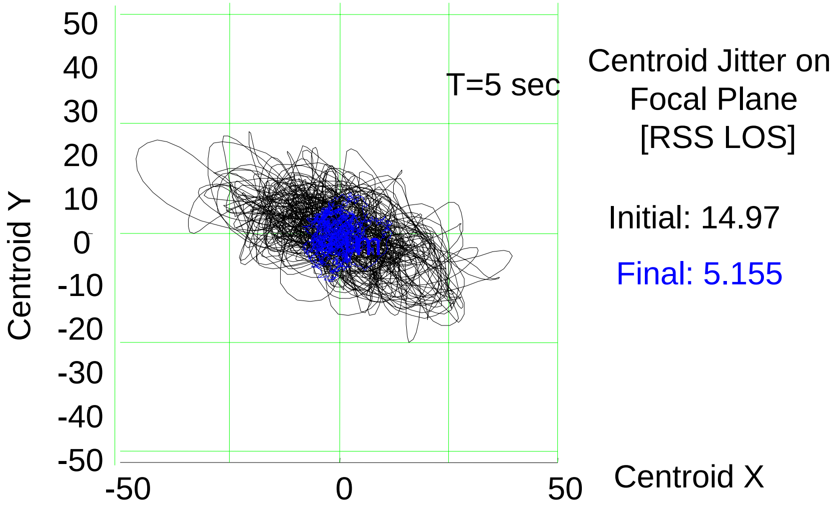


Goal: **Find a "balanced" system design, where the flexible structure, the optics and the control systems work together to achieve a desired pointing performance, given various constraints**

Example 1c: Spacecraft Design



Variables	Initial	Final	
Ru	3000	3845	[RPM]
Us	1.8	1.45	[gcm]
Ud	60	47.2	[gcm^2]
Qc	0.005	0.014	[-]
Tgs	0.040	0.196	[sec]
KrISO	3000	2546	[Nm/rad]
Kzpet	0.9E+8	8.9E+8	[N/m]
tsp	0.003	0.003	[m]
Mgs	15	18.6	[Mag]
Kcf	2E+3	4.7E+5	[-]



Centroid Jitter on
Focal Plane
[RSS LOS]

Initial: 14.97

Final: 5.155

Improvements are achieved by a well balanced mix of changes in the disturbance parameters, structural redesign and increase in control gain of the FSM fine pointing loop.

Examples Architecting vs Design

(US Air Force Photo)

Requirements: Service ceiling, endurance, range weapons loading capability, RCS

Architecture: V-Tail versus single vertical, twin or single engine, # of weapon stations

Design: Thrust to weight ratio, maximum TEF deflection angle, wing NACA profile,...

...

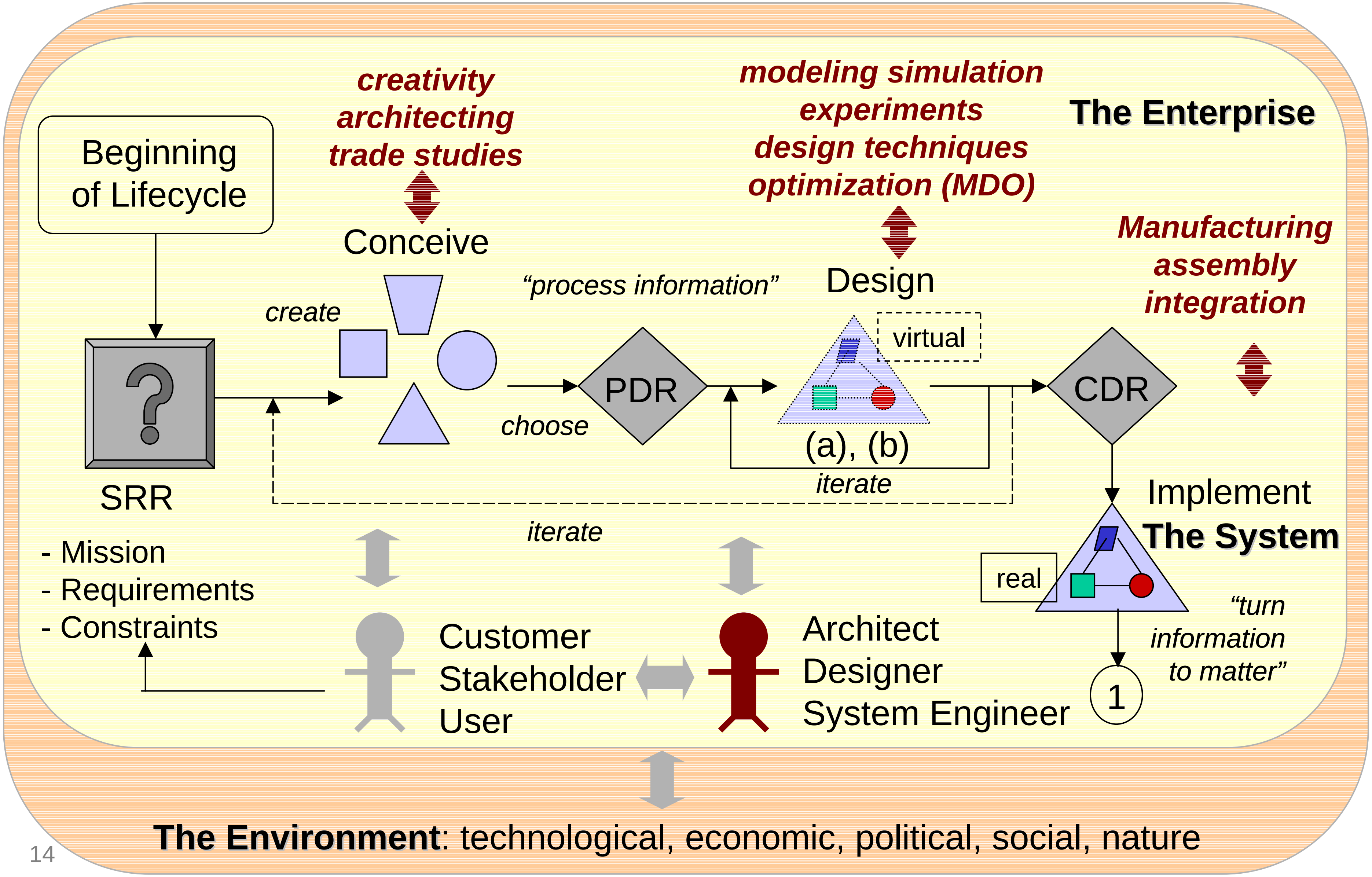
(Swedish State Railways)

Requirements: # passengers per route and day, lbs. of cargo miles, average cruise speed

Architecture: Tilting Mechanism versus track radius, # of cars per composition, Electrical versus Diesel

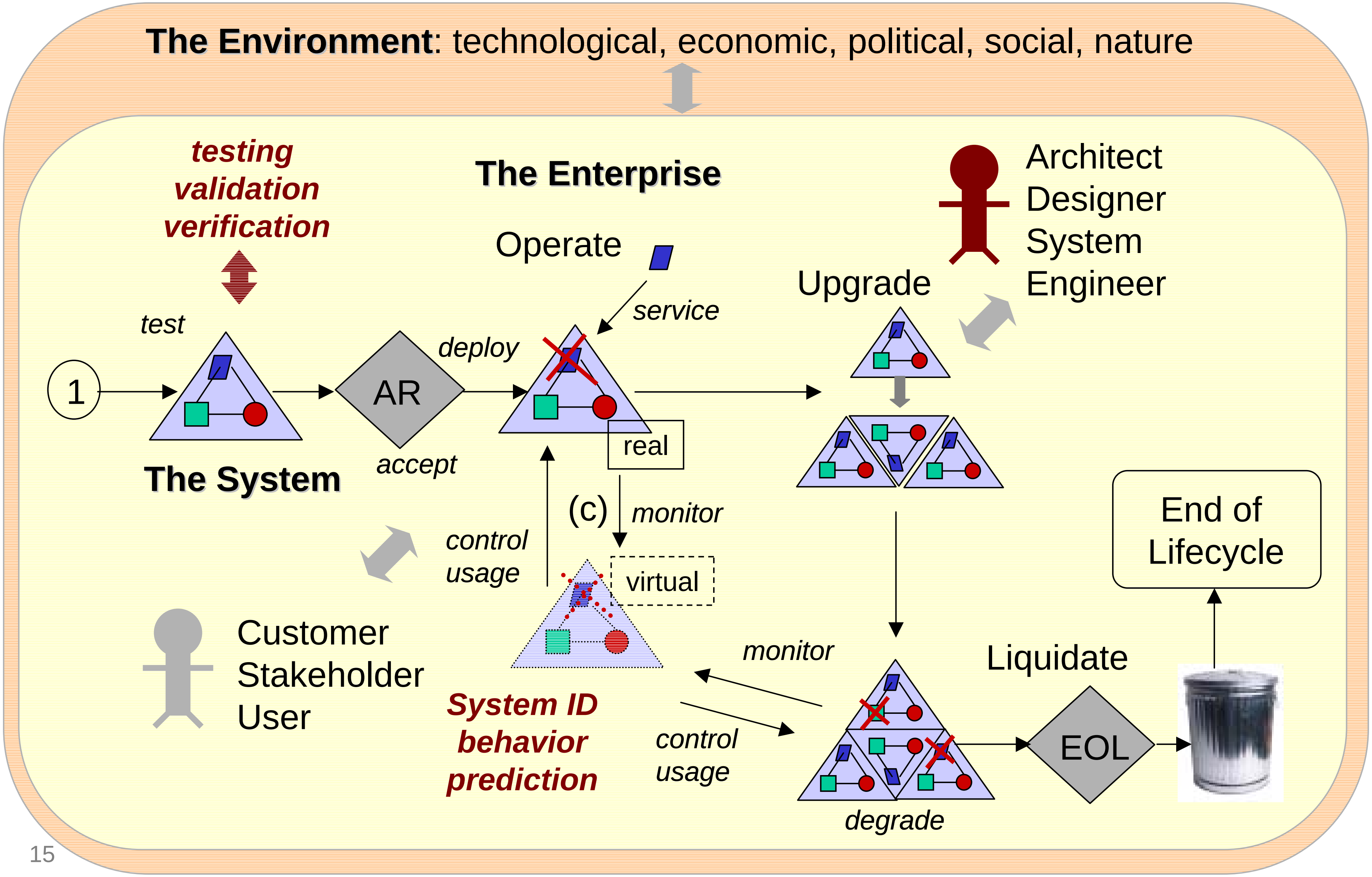
Design: Locomotive power [kW], max tilt angle, suspension control design, seating arrangement

PDP - Part 1



The Environment: technological, economic, political, social, nature

PDP - Part 2



The Environment: technological, economic, political, social, nature

The Enterprise

testing
validation
verification

1

test

The System

AR

deploy

accept

Operate

service

real

(c)

monitor

control
usage

virtual

System ID
behavior
prediction

Upgrade

Architect
Designer
System
Engineer

Customer
Stakeholder
User

monitor

control
usage

degrade

Liquidate

EOL

End of
Lifecycle

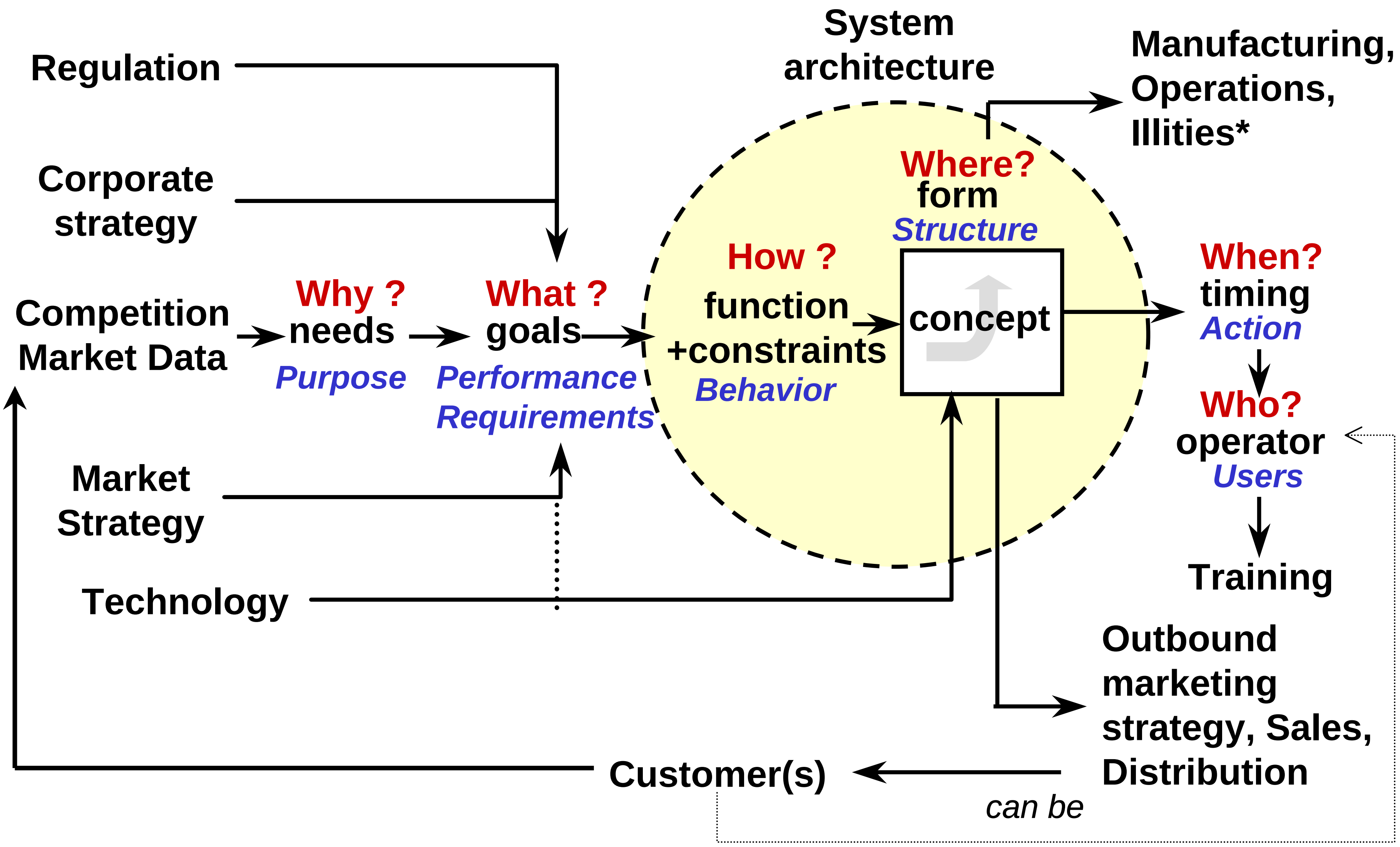
What is System Architecture?

- The structure, arrangements or configuration of system elements and their internal relationships necessary to satisfy constraints and requirements. (Boppe)

- The arrangement of the functional elements into physical blocks. (Ulrich & Eppinger)

- The embodiment of concept, and the allocation of functionality and definition of interfaces among the elements. (Crawley)

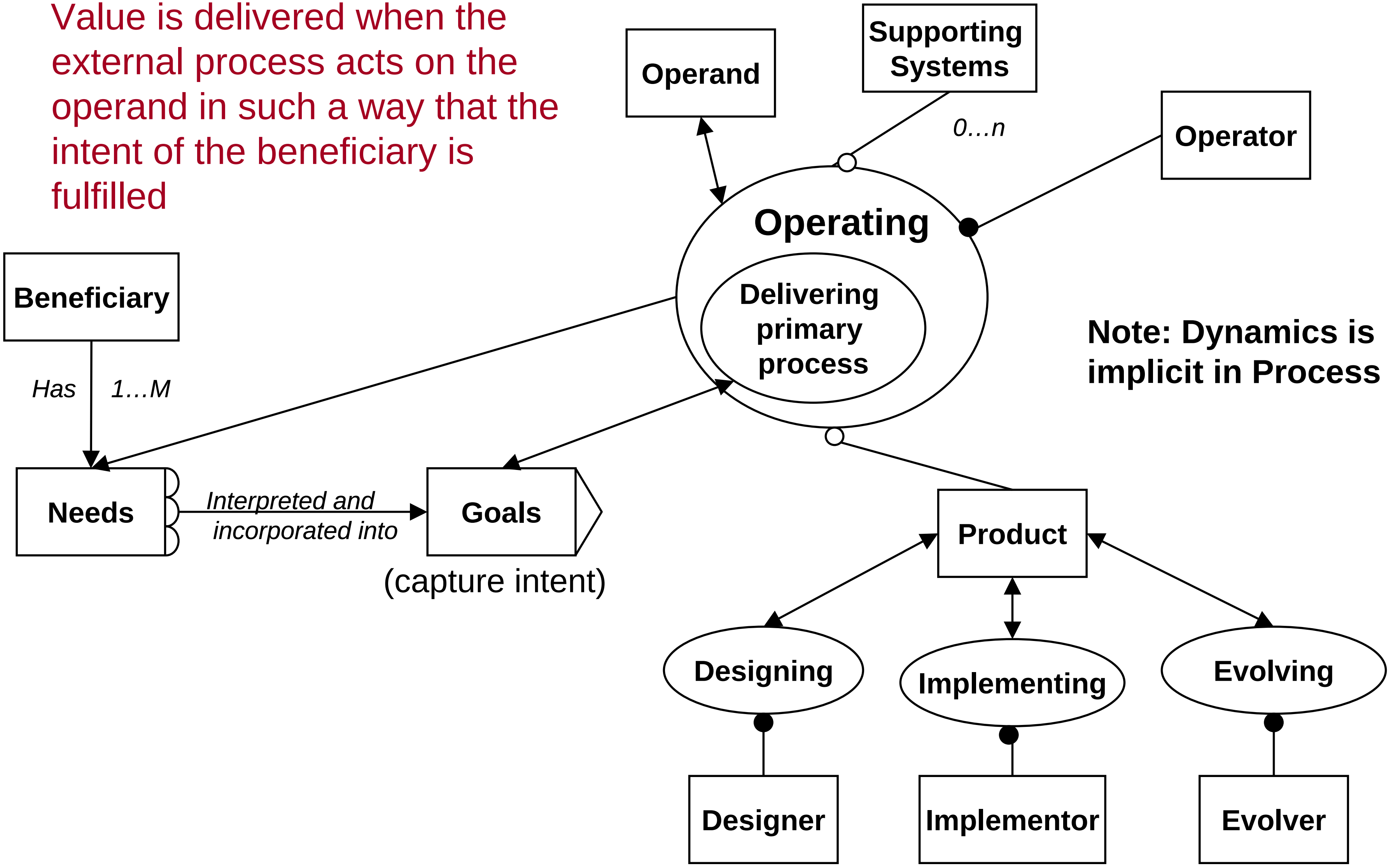
ESD.34 SA Framework



*Reliability, Servicability,Environmental Impact, Upgradeability, Flexibility,etc…

OPM Product Attributes

Value is delivered when the external process acts on the operand in such a way that the intent of the beneficiary is fulfilled



(capture intent)

Note: Dynamics is implicit in Process

Role of System Architect

- The architect performs the most abstract, high level function in product development
- The architect is the driving force of the conceptual phase
- The architect
  - Defines the boundaries and functions
  - Creates the Concept
  - Allocates functionality and defines interfaces and abstractions
  - The architect is not a generalist, but a specialist in simplifying complexity, resolving ambiguity and focusing creativity

Advanced Topics:

- Legacy Systems and Reuse
- Supply Chain Impact
- Platforms and Product Families

What is M(S)DO ?

- A methodology for the design of complex engineering systems and subsystems that coherently exploits the synergism of mutually interacting phenomena
- Optimal design of complex engineering systems which requires analysis that accounts for interactions amongst the disciplines (= parts of the system)
- “How to decide what to change, and to what extent to change it, when everything influences everything else.”

Ref: AIAA MDO website http://endo.sandia.gov/AIAA_MDOTC/main.html

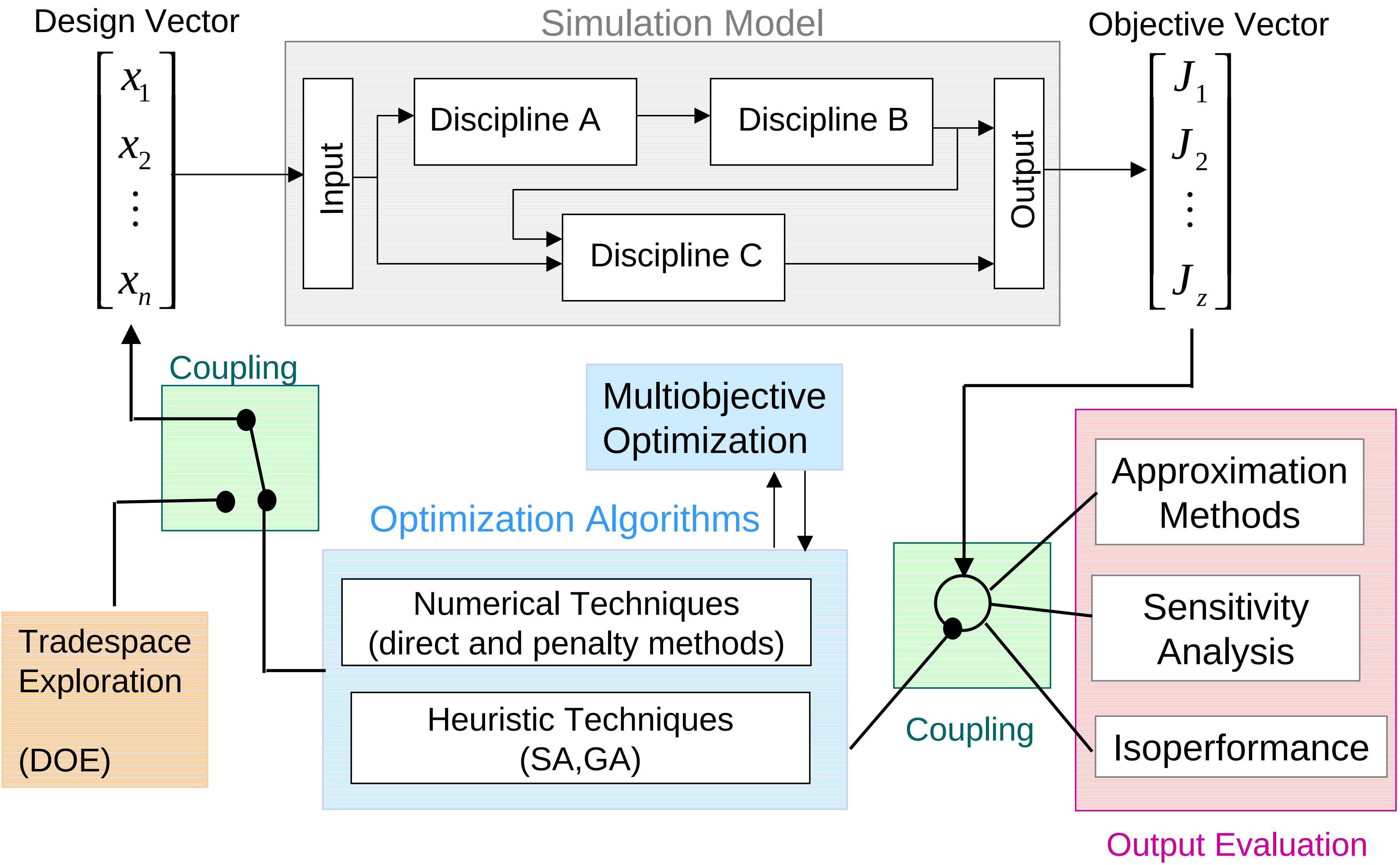
System Level Optimization

Why system-level, multidisciplinary optimization ?

- Disciplinary specialists tend to strive towards improvement of objectives and satisfaction of constraints in terms of the variables of their own discipline
- In doing so they generate side effects - often unknowingly- that other disciplines have to absorb, usually to the detriment of the overall system performance

Example: High wing aspect ratio aircraft designs

ESD.77J Framework



Design Vector

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$$

Simulation Model

Input

Discipline A

Discipline B

Discipline C

Output

Objective Vector

$$\begin{bmatrix} J_1 \\ J_2 \\ \vdots \\ J_z \end{bmatrix}$$

Coupling

Multiobjective Optimization

Optimization Algorithms

Numerical Techniques (direct and penalty methods)

Heuristic Techniques (SA,GA)

Tradespace Exploration

(DOE)

Coupling

Approximation Methods

Sensitivity Analysis

Isoperformance

Output Evaluation

MSDO 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?

Fidelity versus Expense

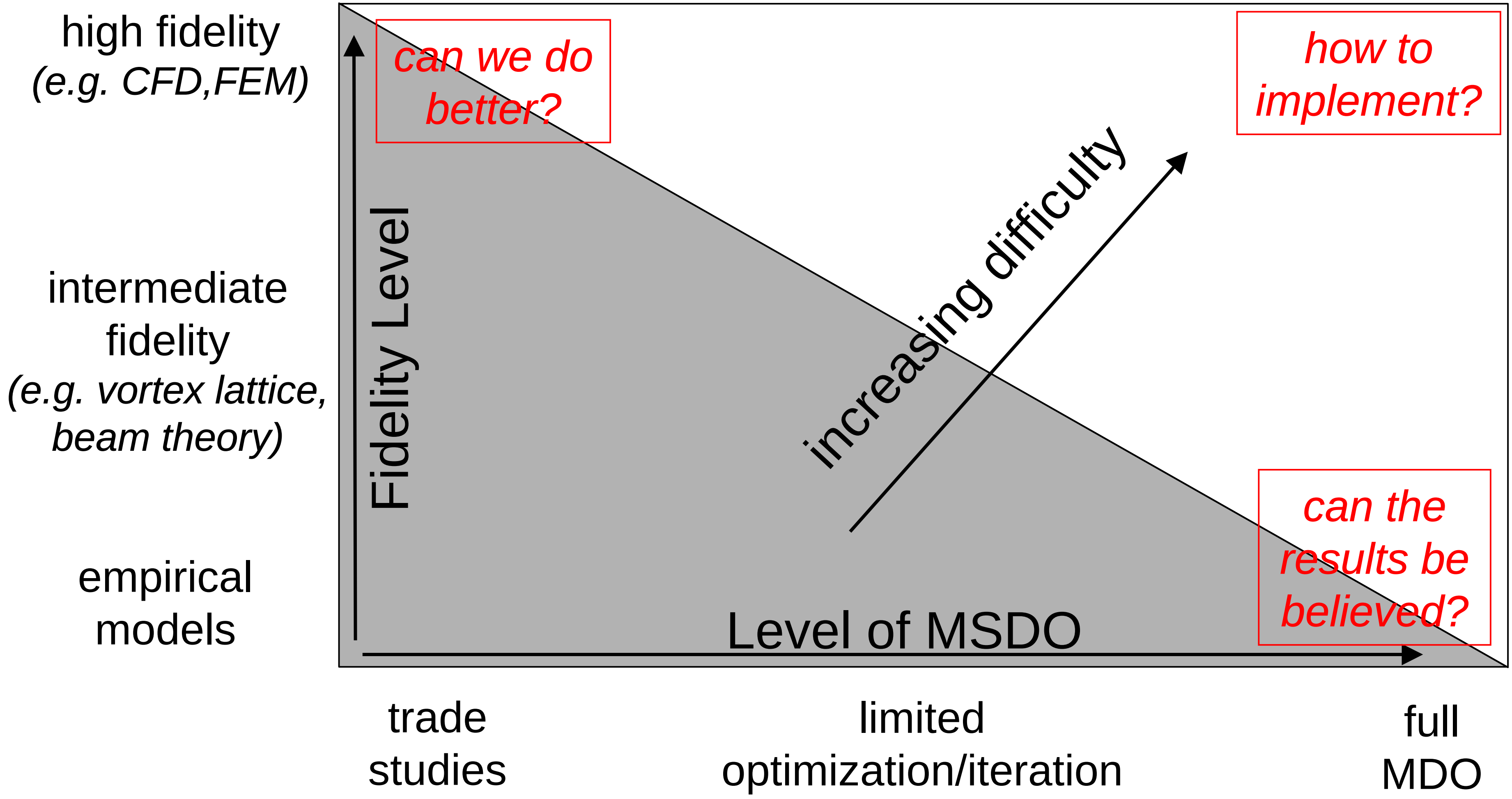
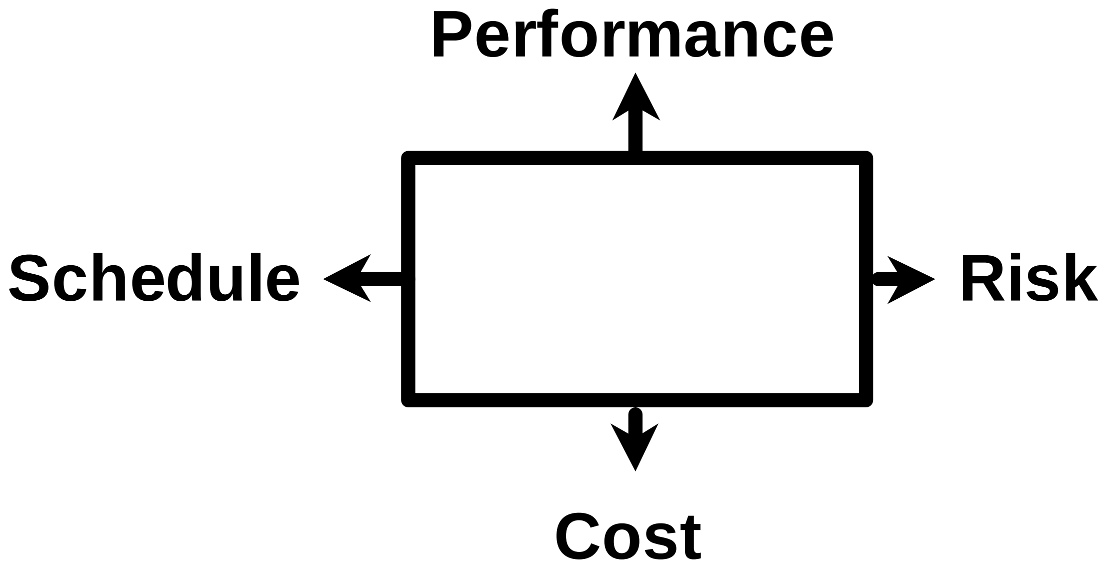


Diagram adapted by the author from Giesing, J.P., Barthelemy, J.-F.M., A Summary of Industry MDO Applications and Needs, AIAA Paper 98-4737, Presented at VIIth AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Optimization and Analysis, St. Louis, MO, Sep. 1998.

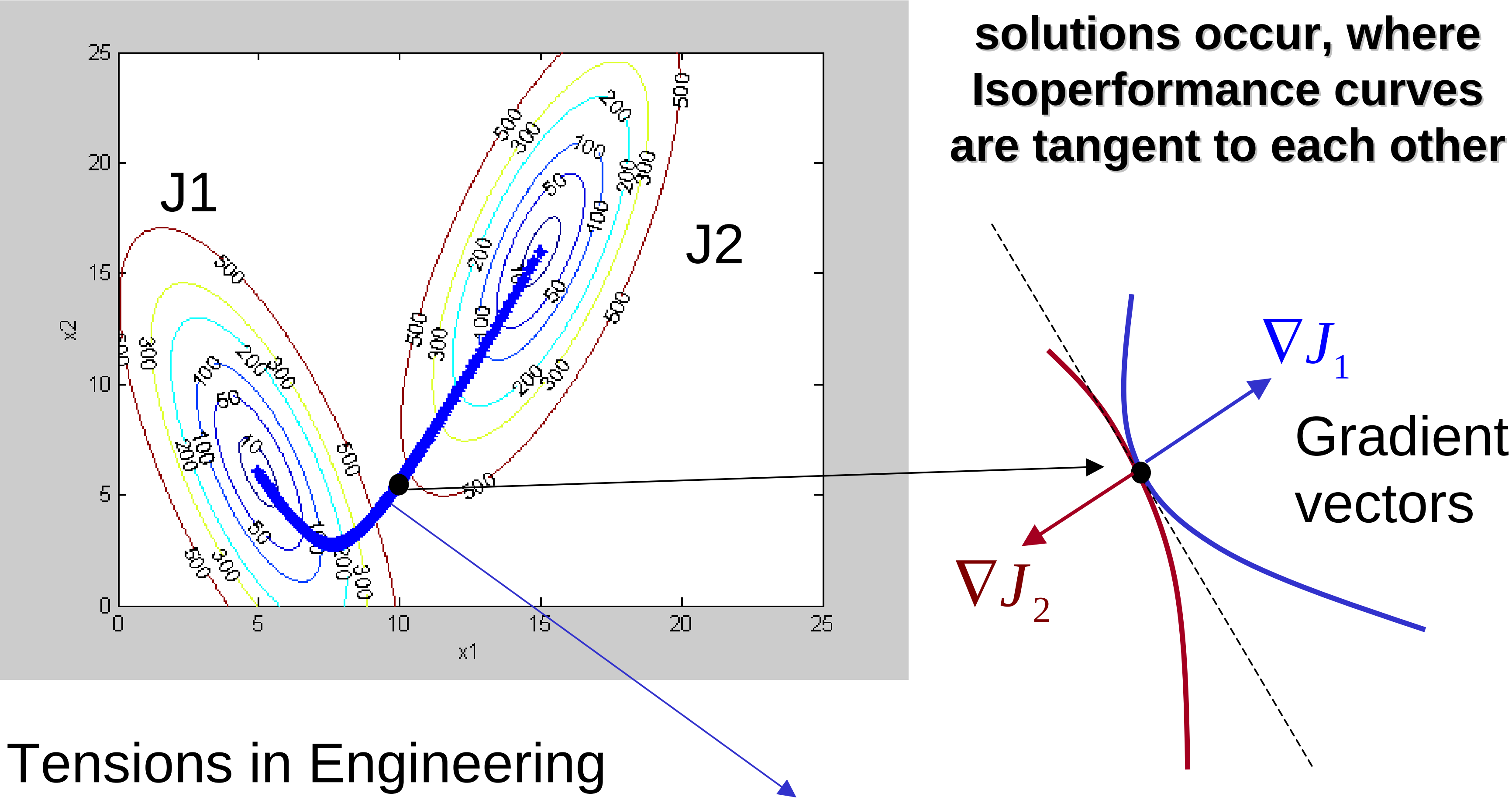
Competing Tensions



Ref: Maier, Mark W., Rechtin, Eberhardt, "The Art of Systems Architecting", 2nd Edition, CRC Press, 2000

Multiobjective Optimization and Isoperformance

Non-dominated solutions occur, where Isoperformance curves are tangent to each other



Gradient vectors

Pareto-optimal Curve

Tensions in Engineering System Design can be quantified

Conclusions

- Engineering Systems have to be designed and “optimized” for multiple objectives beyond performance
- We should consider not just single, “optimal” point designs but families of Pareto-optimal designs that achieve similar performance
- Good Engineering Systems are “balanced” and achieve their performance by evenly distributing the burden among subsystems
- Inherent tradeoffs between performance, cost and risk need to be made explicit and should be resolved in a deliberate manner

Research Agenda

- What multiobjective methods are most suitable for Engineering Systems ?
- How to quantify Illities (e.g. Flexibility) and other criteria that resist quantification
- Understand the role of Constraints (e.g. Technology Infusion)
- Learn from position of past or existing systems in the trade space (e.g. B-52 vs B-58) - what would we do differently today?
- Establish a generic set of objective metrics related to functional classification of Engineering Systems
- How to leverage optimization during CONCEPTUAL design phase?