Fundamentals of Systems Engineering

Prof. Olivier L. de Weck

Session 11
Lifecycle Management

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
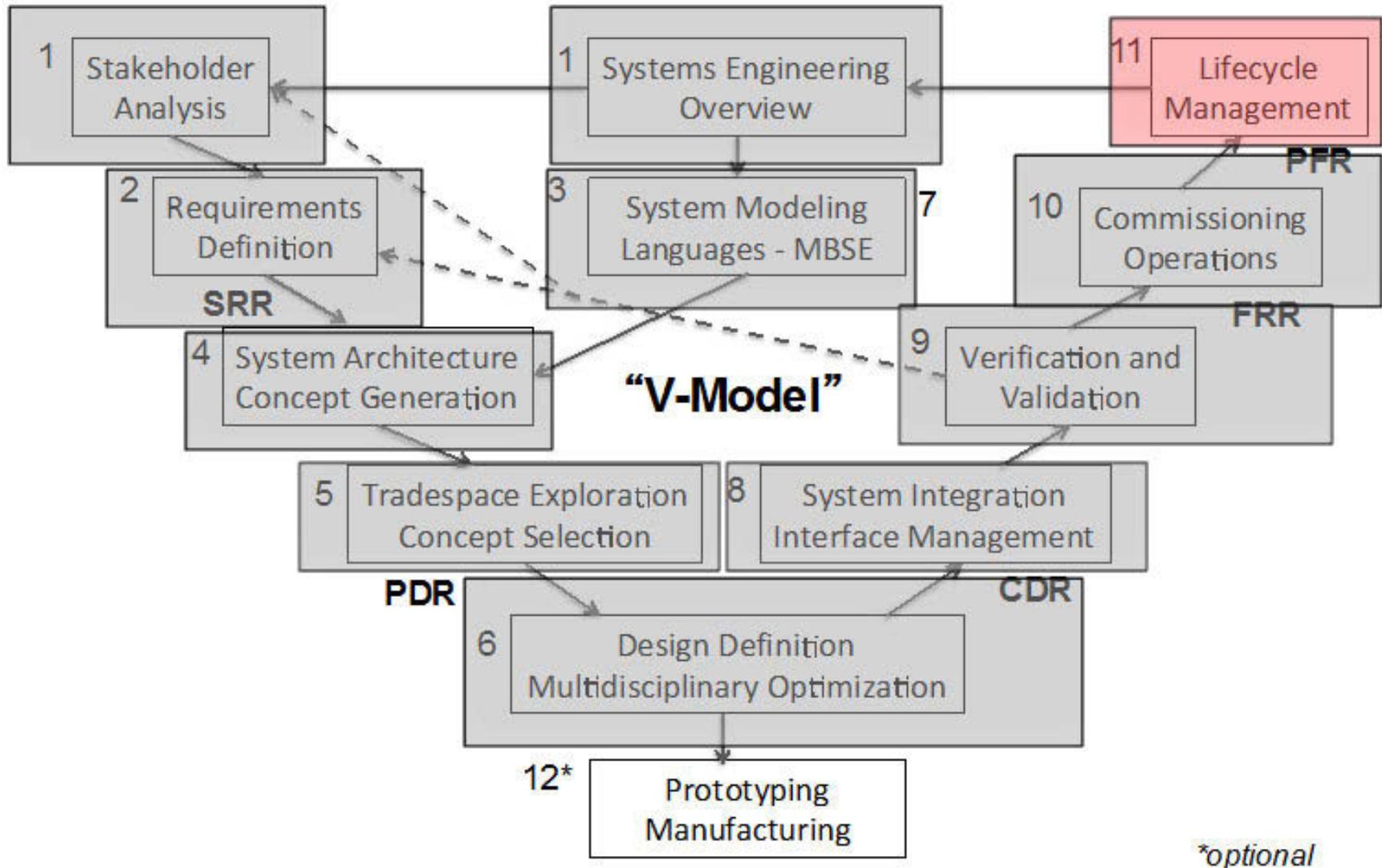
1 Stakeholder Analysis

2 Requirements Definition
SRR

4 System Architecture Concept Generation

5 Tradespace Exploration Concept Selection
PDR

6 Design Definition Multidisciplinary Optimization

1 Systems Engineering Overview

3 System Modeling Languages - MBSE

7

"V-Model"

8 System Integration Interface Management
CDR

12* Prototyping Manufacturing

11 Lifecycle Management
PFR

10 Commissioning Operations
FRR

9 Verification and Validation

*optional

Numbers indicate the session # in this class

3

Outline for Today

- Definition of Lifecycle Management

- Lifecycle Properties, i.e. the "Illities"

- A Case Study
  - Reconfiguration of Communications Satellite Constellations

- Summary of Key Concepts taught in this class

- Career / Study Recommendations regarding SE

Lifecycle Management

- **Lifecycle Management** is the active engagement of all stakeholders with a system between the time when it first starts to operate until the time of its decommissioning, in order to maximize the value gained from the system's existence. Lifecycle management starts from the beginning.

- Lifecycle Management can include activities such as:
  - Daily Operations and Monitoring
  - Training and Certification of Operators
  - Servicing, incl. Preventative and Corrective Maintenance
  - Dealing with small and large failures, recalls, anomalies etc…
  - Protecting the system from random or targeted attacks (cyber-physical)
  - Sharing and archiving the data produced by the system
  - Upgrading and retrofitting the system as needed
  - Cross-strapping the system with other systems in a federation of systems
  - Reducing the resource consumption and environmental burden
  - Decommissioning the system when it is time to do so
  - Etc..
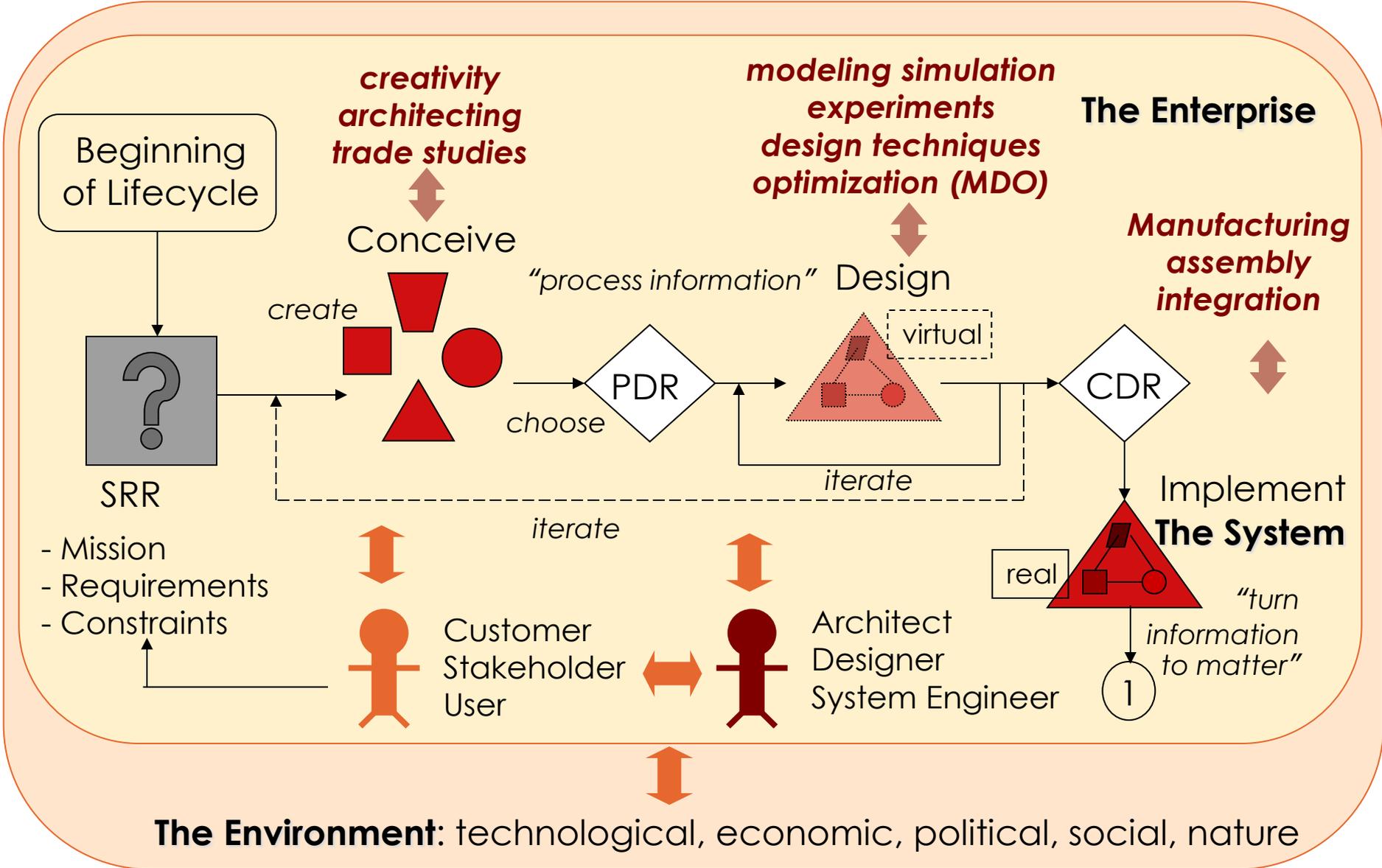
The Environment: technological, economic, political, social, nature

The Enterprise

testing
validation
verification

Operate

Architect
Designer
System
Engineer

test

Upgrade

1

AR

deploy

service

accept

real

control
usage

monitor

The System

virtual

Customer
Stakeholder
User

System ID
behavior
prediction

monitor

Liquidate

End of
Lifecycle

control
usage

EOL

degrade
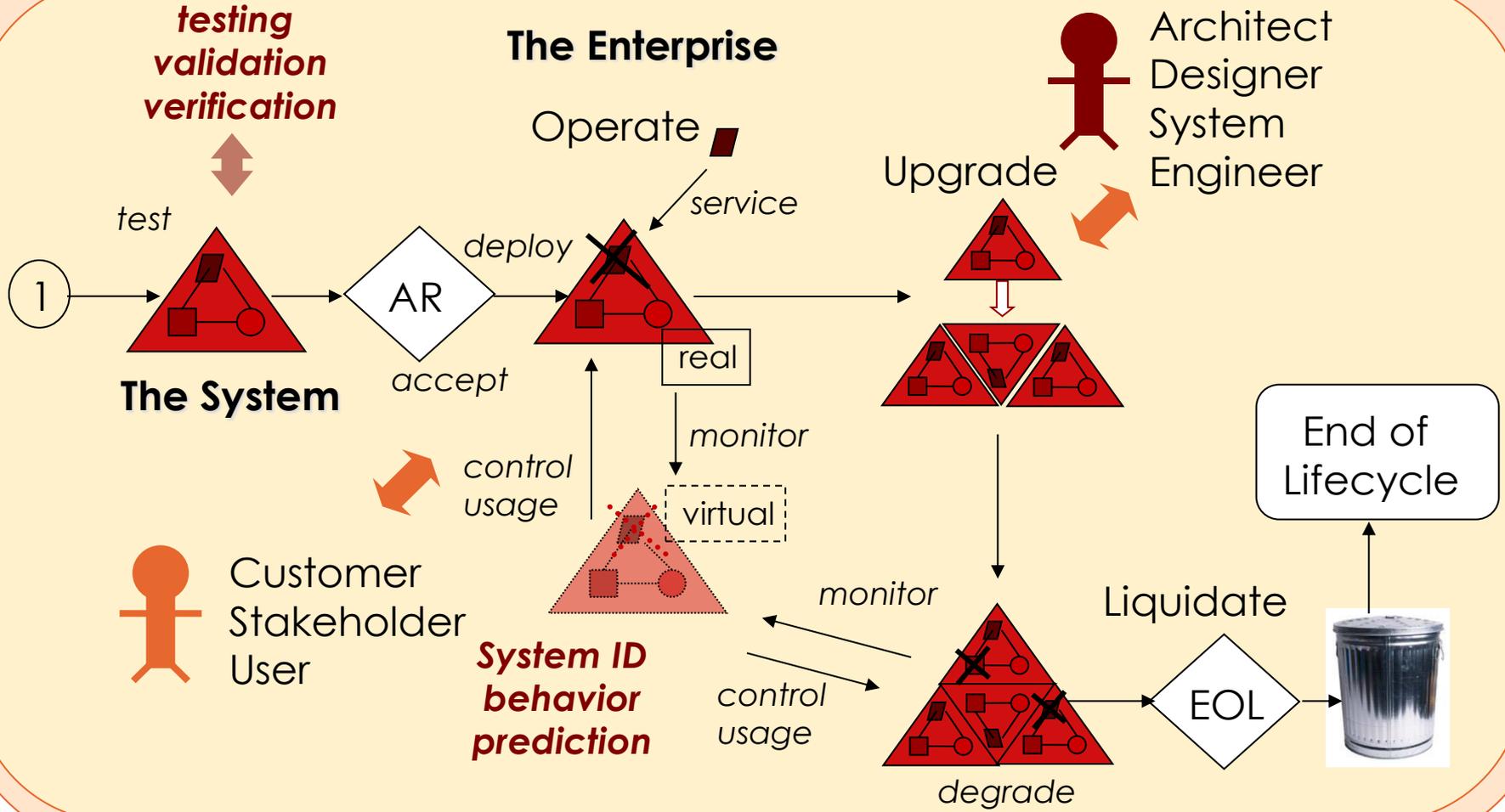
Space Shuttle Lifecycle (1971-2011)

A COSTLY ENTERPRISE — **$192B Total, 135 launches**

The average cost per launch was about $1.5 billion over the life of the US space-shuttle programme.
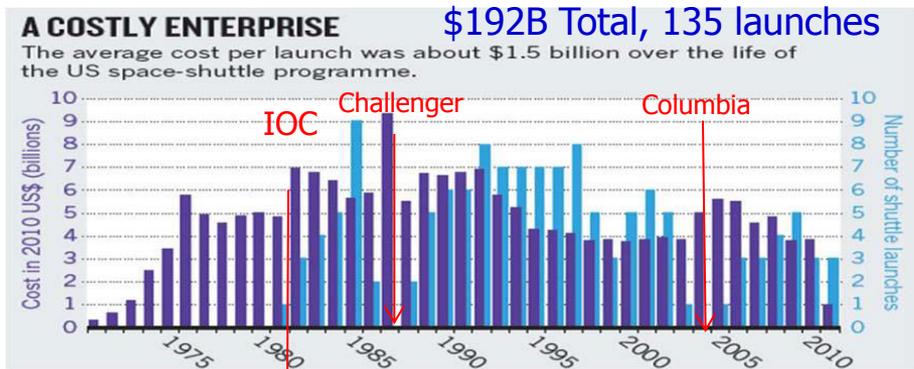
Roger Pielke Jr & Radford Byerly, Shuttle programme lifetime cost, *Nature* 472, 38 (07 April 2011)

Reprinted by permission from Macmillan Publishers Ltd: Nature. Source: Figure of "A Costly Enterprise" in Pielke Jr, Roger, and Radford Byerly, "Shuttle programme lifetime cost." *Nature* 472, 38. © 2011.

C > **D** > **I** > **O**

system architecture · design · testing manufacturing · operations

- Vision: partially reusable space vehicle with quick turnaround and high flight rate
- Actual: complex and fragile vehicle with average cost of about $1.5B/flight (20,000 workforce)
- Why?
  - Overoptimism
  - Congress capped RDT&E at $B5.15 (1971)
    - Focus on achieving launch performance (24 mt LEO)
    - Maintainability needed to be "designed-in"
    - No realistic lifecycle cost/value optimization done

What we wanted

This image is in the public domain.

What we got
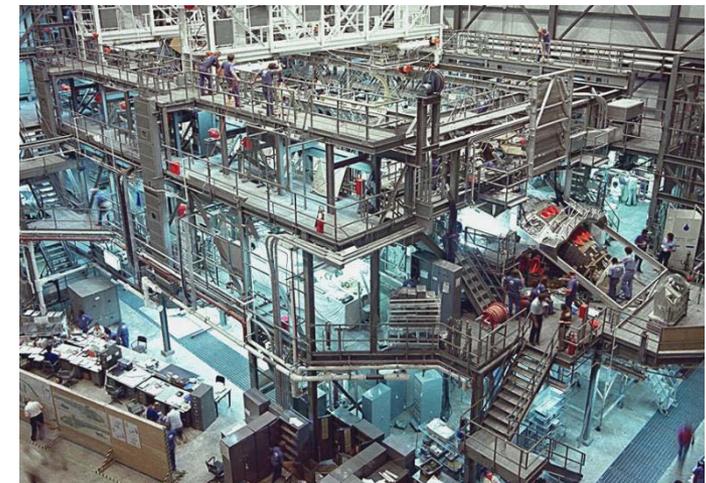
This image is in the public domain.

ISO 15288 – Most important standard for lifecycle

System Life Cycle Processes

Agreement Processes

- Acquisition Process (Clause 6.1.1)
- Supply Process (Clause 6.1.2)

Organizational Project-Enabling Processes

- Life Cycle Model Management Process (Clause 6.2.1)
- Infrastructure Management Process (Clause 6.2.2)
- Project Portfolio Management Process (Clause 6.2.3)
- Human Resource Management Process (Clause 6.2.4)
- Quality Management Process (Clause 6.2.5)

Project Processes

- Project Planning Process (Clause 6.3.1)
- Project Assessment and Control Process (Clause 6.3.2)
- Decision Management Process (Clause 6.3.3)
- Risk Management Process (Clause 6.3.4)
- Configuration Management Process (Clause 6.3.5)
- Information Management Process (Clause 6.3.6)
- Measurement Process (Clause 6.3.7)

Technical Processes

- Stakeholder Requirements Definition Process (Clause 6.4.1)
- Requirements Analysis Process (Clause 6.4.2)
- Architectural Design Process (Clause 6.4.3)
- Implementation Process (Clause 6.4.4)
- Integration Process (Clause 6.4.5)
- Verification Process (Clause 6.4.6)
- Transition Process (Clause 6.4.7)
- Validation Process (Clause 6.4.8)
- Operation Process (Clause 6.4.9)
- Maintenance Process (Clause 6.4.10)
- Disposal Process (Clause 6.4.11)

Figure 4 — The system life cycle processes

INTERNATIONAL STANDARD

ISO/IEC 15288

IEEE Std 15288-2008

Second edition 2008-02-01

Systems and software engineering — System life cycle processes

Ingénierie des systèmes et du logiciel — Processus du cycle de vie du système

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Reference Paper

- de Weck O.L., Ross A., Rhodes D., "*Investigating Relationships and Semantic Sets amongst System Lifecycle Properties (Ilities)*", 3rd International Engineering Systems Symposium, CESUN 2012, TU Delft, The Netherlands, June 18-20, 2012

What are the "Illities"?

- **Complex Engineering Systems live for decades or centuries**

- The *ilities* are desired properties of systems, such as flexibility or maintainability (usually but not always ending in "ility") that often manifest themselves after a system has been put to initial use.

- These properties are not the primary functional requirements of a system's performance, but typically concern wider system impacts with respect to time and stakeholders than embodied in those primary functional requirements
  - Most research has looked at the Illities – one at a time.

- Research Questions:
  - **What are the most prevalent or most important (top 20) Ilities in the scientific literature and in common use?**
  - **What are the relationships amongst Ilities? Do they form semantic sets?**
  - **Can we use this information for better system design?**

- Approach:
  - Method 1: Prevalence Analysis using Literature/Web Survey
  - Method 2: Human Cognitive Experiments using Hierarchy Exercise

Prevalence Analysis

Journal Articles from Compendex/Inspec Databases between 1884 and 2010

13
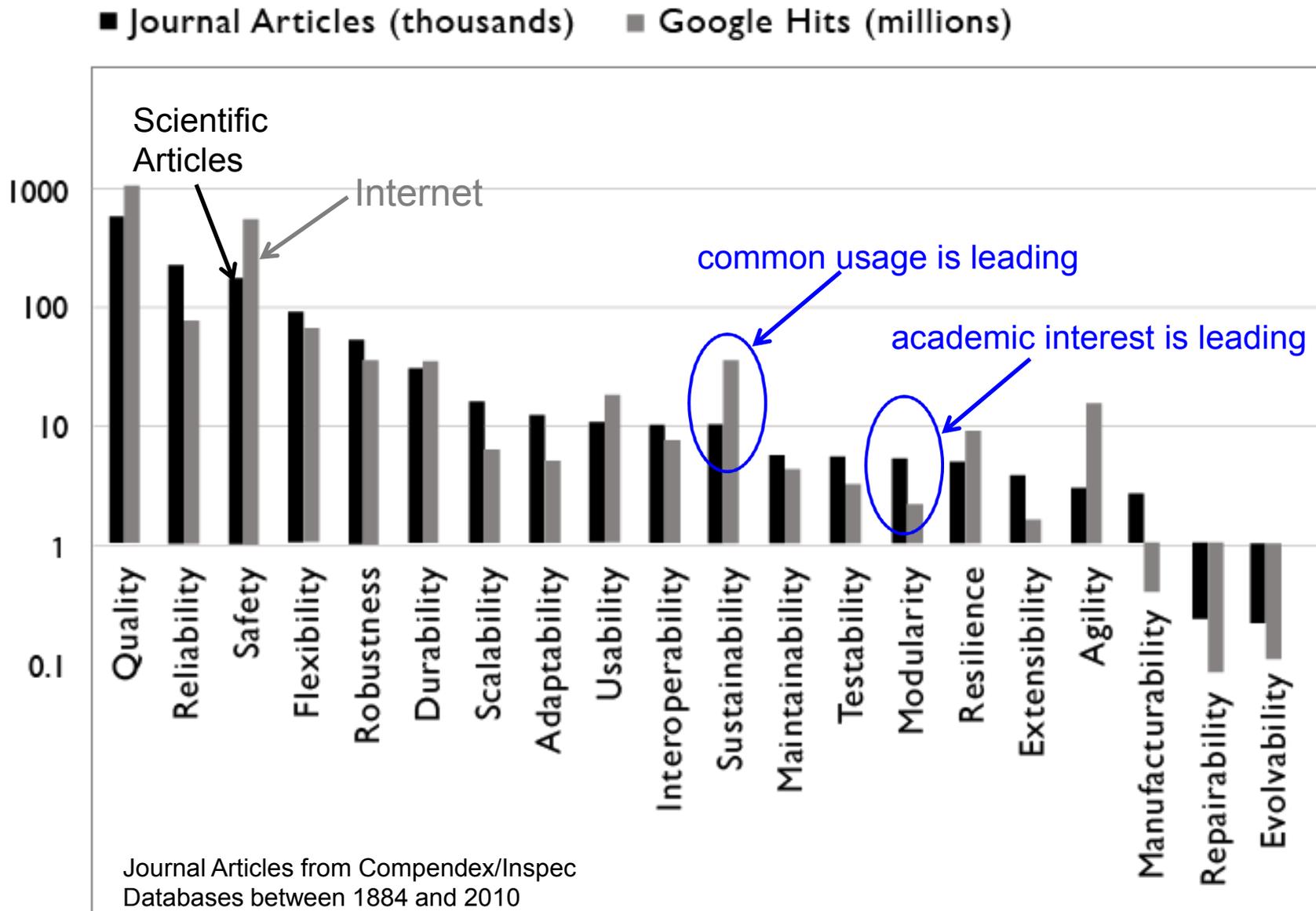
Cumulative Research in Ilities over Time

Cumulative number of journal articles where an Ility appears in the title or abstract of the paper (1884-2010). Source: Inspec and Compendex, accessed via Engineering Village http://www.engineeringvillage.com
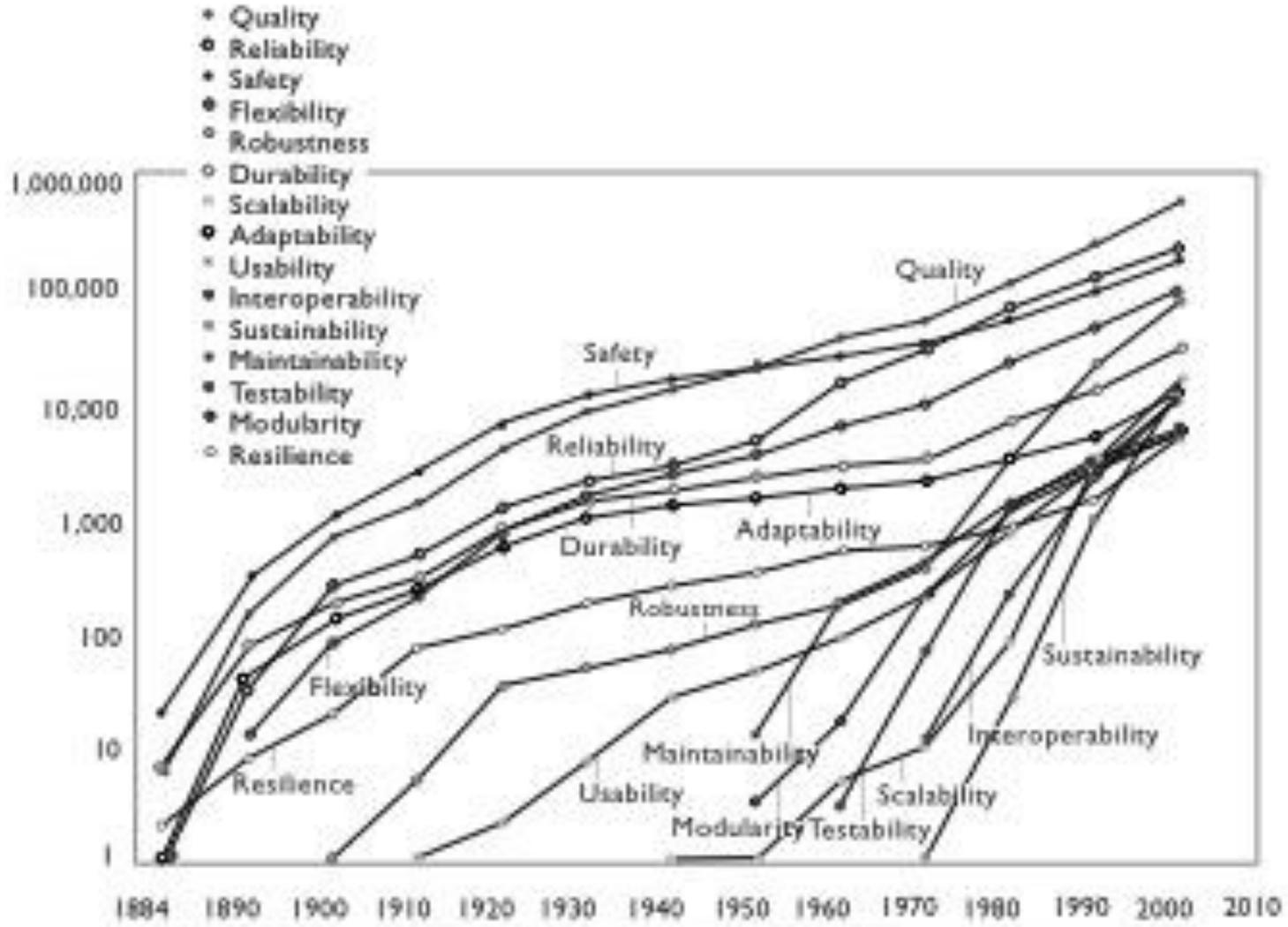
Fig. 4-2

Line weight reflects strength of relationships

Made well with high quality in early life

Easy to change system configuration

Performs well over time under uncertainty

Cutoff value for edge strength is 0.1
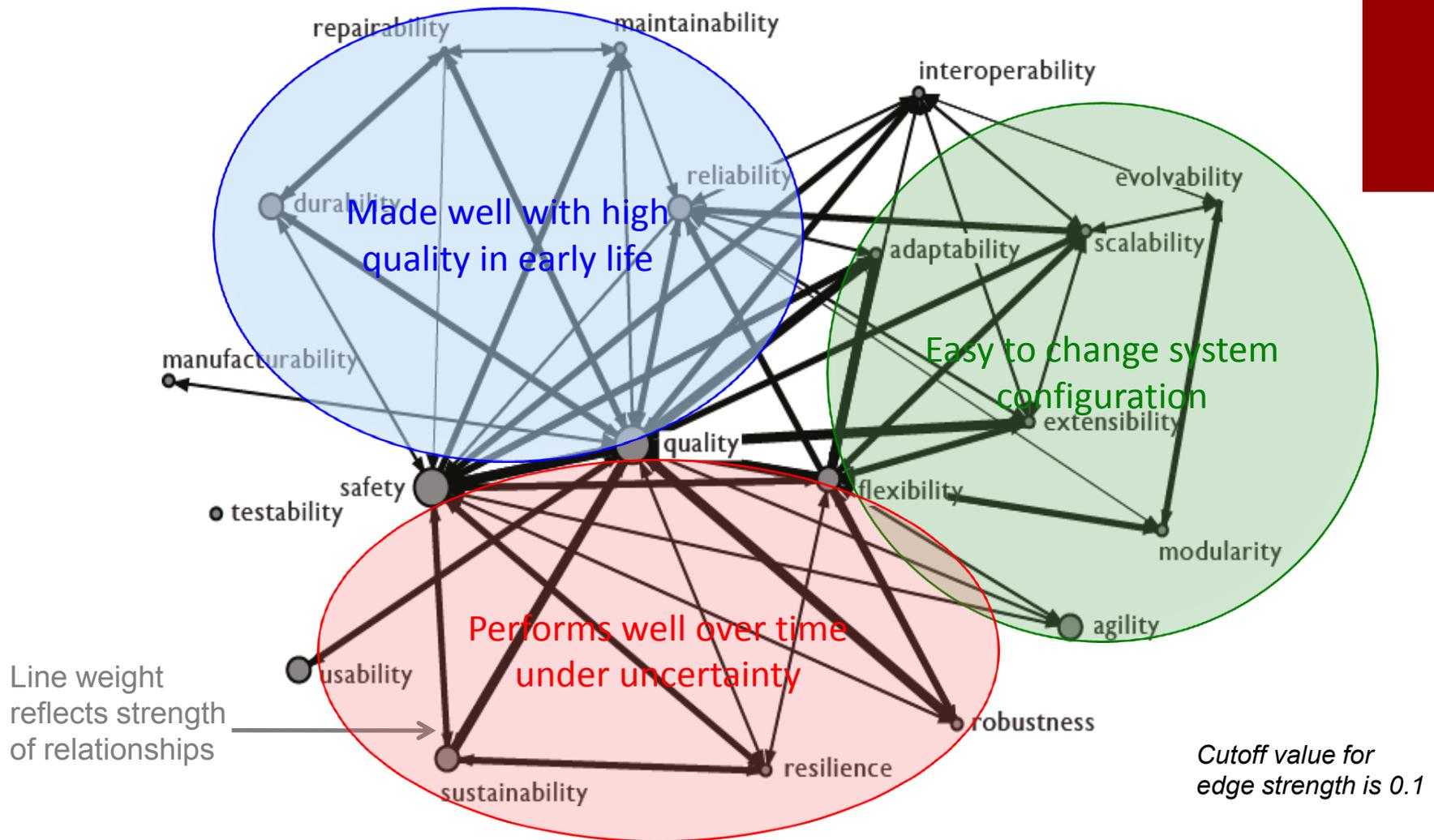
Network structure with classical engineering ilities at the core and newer emerging ones at the periphery based on co-occurrence

Source: web keyword 2-tupel correlation analysis, August 2010

2: Human "Experiments" with Hierarchy

- Humans have deep, but possibly varied, semantic notions of a hierarchy of Ilities

  - Elicit means-ends-hierarchy through direct elicitation and group discussion and interviews

  - Two rounds

  - **Round 1**: 4 groups with 2-4 members each. Find parent-child relationships. Describe means → ends relations

  - Interviews

  - **Round 2:** Revise group findings based on inputs from other groups at the end of round 1

  - Constructed combined means-ends hierarchy

12 experienced system designers and researchers were presented with a list of 15 ilities like this one

Ility Name	Definition ("ability of a system…")
adaptability	to be changed by a system-internal change agent with intent
agility	to change in a timely fashion
changeability	to alter its operations or form, and consequently possibly its function, at an acceptable level of resources
evolvability	design to be inherited and changed across generations (over time)
extensibility	to accommodate new features after design
flexibility	to be changed by a system-external change agent with intent
interoperability	to effectively interact with other systems
modifiability	to change the current set of specified system parameters
modularity	degree to which a system is composed of modules (not an ability-type ility)
reconfigurability	to change its component arrangement and links reversibly
robustness	to maintain its level and/or set of specified parameters in the context of changing system external and internal forces
scalability	to change the current level of a specified system parameter
survivability	to minimize the impact of a finite duration disturbance on value delivery
value robustness	to maintain value delivery in spite of changes in needs or context
versatility	to satisfy diverse needs for the system without having to change form (measure of latent value)

What is their relationship?
Do they form a hierarchy?

Group 1
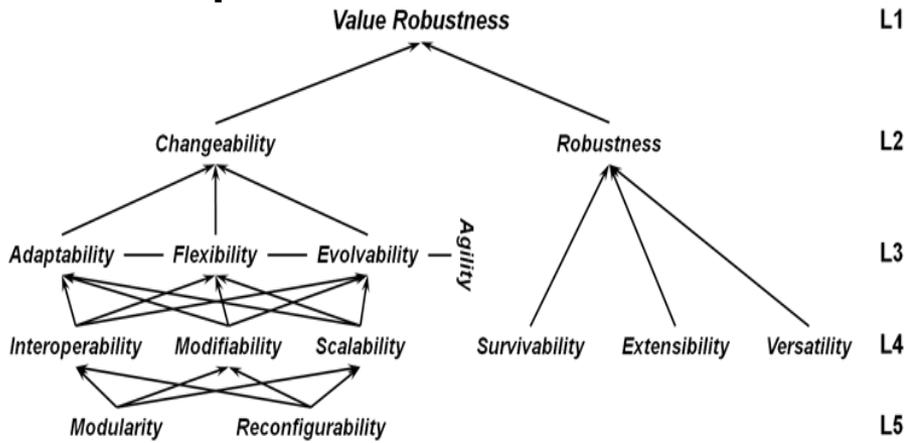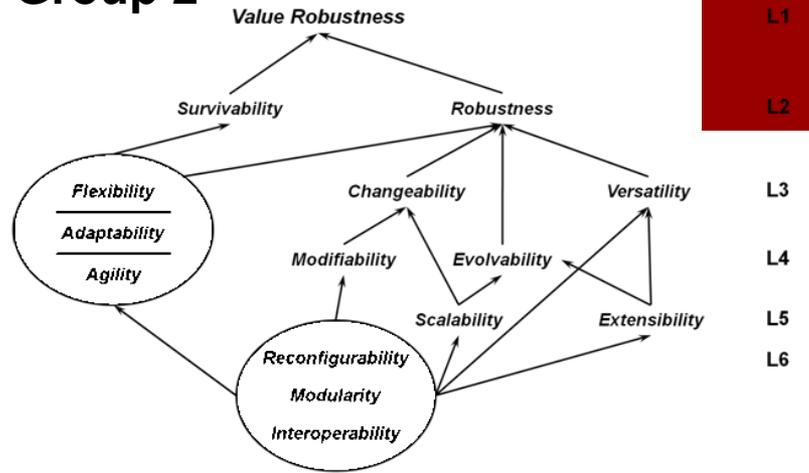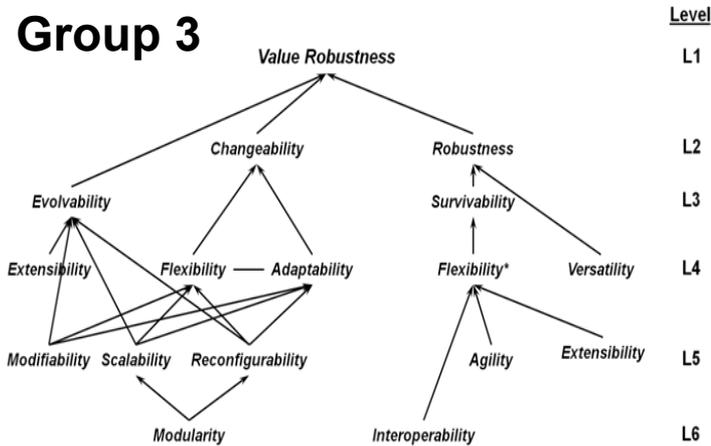
Group 2

Group 3

Group 4
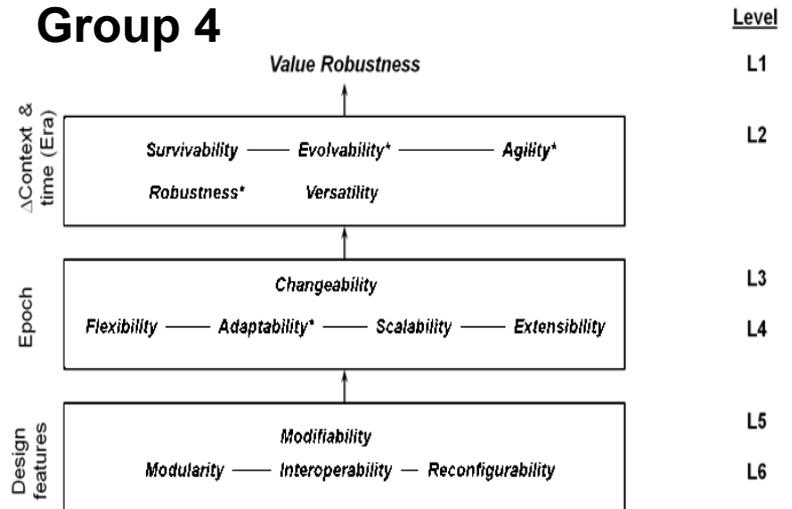
Combined Means to Ends Hierarchy
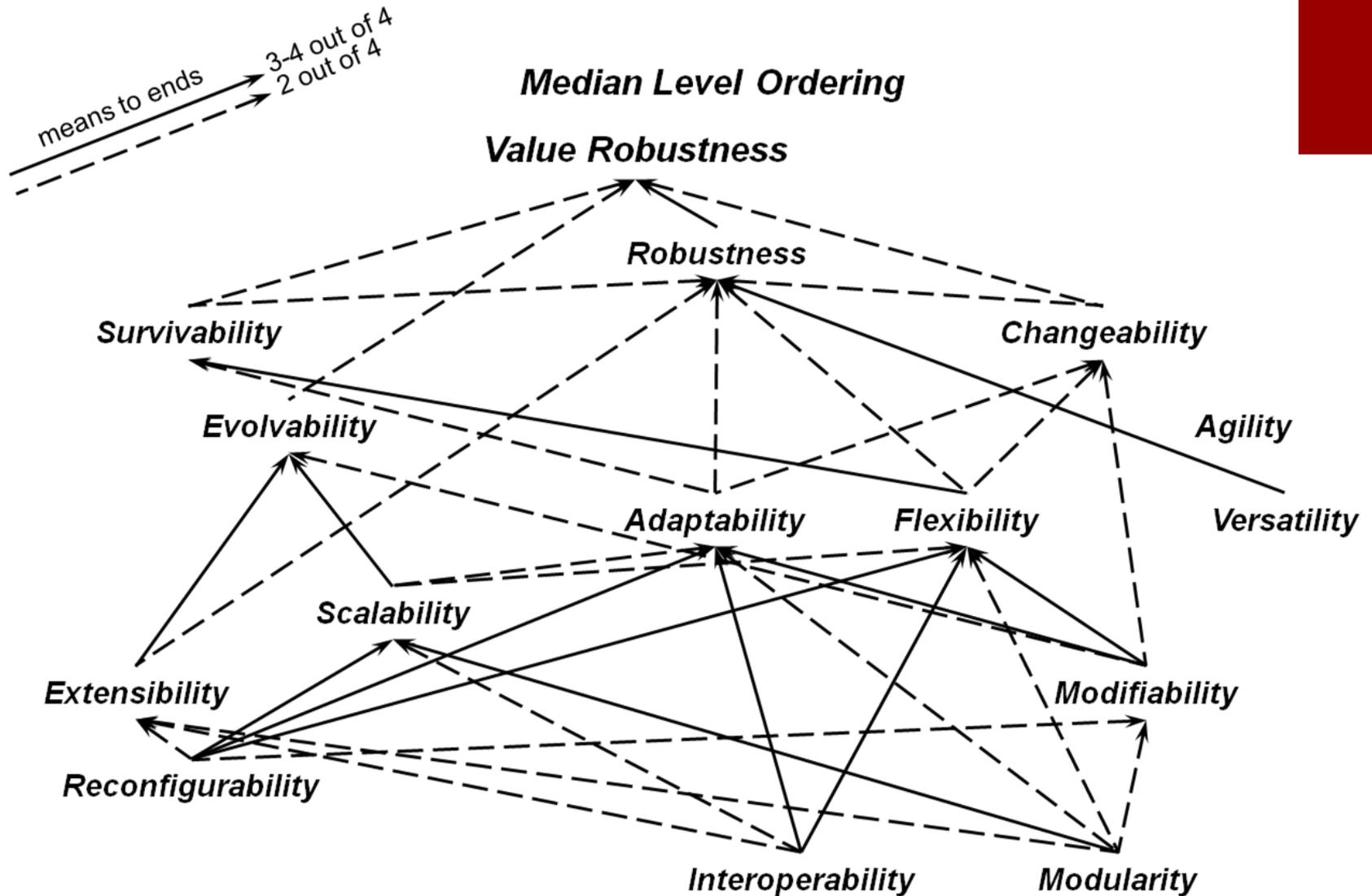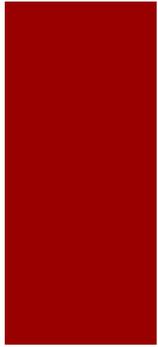
Summary of Lifecycle Properties
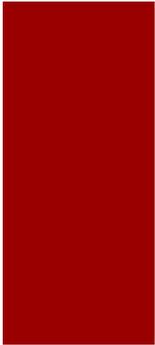
- Lifecycle properties (Ilities) are critical for long term value

- Despite differences, the two methods led to similar high-level conclusions regarding the relationships amongst Ilities:
  - Some ilities are closely related to each other and form semantic sets that are tied together by both synonymy and polysemy relationships.
  - System value is heavily driven by the ability of a system to be robust (despite internal and exogenous disturbances), flexible or changeable and resilient or survivable over time.
  - A hierarchy of ilities with two or three levels appears to exist whereby some ilities, such as modularity and interoperability appear at lower levels and serve as enablers of higher level ilities.

- Future work will apply both methods to larger sets of ilities, with larger groups of test subjects and will use consistent sets of ilities

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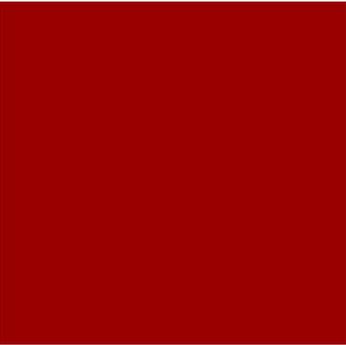
Communications Satellite Constellation Case

- Iridium and Globalstar

- Integrated Lifecycle Modeling

- **Flexibility / Scalability:** Staged Deployment Approach

de Weck, O.L., de Neufville R. and Chaize M., "Staged Deployment of Communications Satellite Constellations in Low Earth Orbit", *Journal of Aerospace Computing, Information, and Communication*, 1 (3), 119-136, March 2004

Existing Big LEO Systems

	Iridium	Globalstar
Time of Launch	1997 – 1998	1998 – 1999
Number of Sats.	66	48
Constellation Formation	polar	Walker
Altitude (km)	780	1414
Sat. Mass (kg)	689	450
Transmitter Power (W)	400	380
Multiple Access Scheme	Multi-frequency – Time Division Multiple Access	Multi-frequency – Code Division Multiple Access
Single Satellite Capacity Global Capacity Cs	1,100 duplex channels 72,600 channels	2,500 duplex channels 120,000 channels
Type of Service	voice and data	voice and data
Average Data Rate per Channel	4.8 kbps	2.4/4.8/9.6 kbps
Total System Cost	$ 5.7 billion	$ 3.3 billion
Current Status	Bankrupt but in operation. IridumNEXT under development (2017)	Bankrupt but in operation. Globalstar now publicly traded and valued at $1.87B

Individual Iridium Satellite

Individual Globalstar Satellite

Motivation: Iridium Satellite System

'Motorola unveils new concept for global personal communications: base is constellation of low-orbit cellular satellites',

Motorola Press Release on Iridium, London, 26 June 1990.

'Last week, Iridium LLC filed for bankruptcy-court protection. Lost investments are estimated at $5 billion.'

Wall Street Journal, New York, 18 August 1999.

- Difficult to properly size capacity of large system

- Market assumptions can change when 7-8 years elapse between conceptual design and fielding (1991-1998)

Iridium Satellite

Bar chart: Millions of subscribers vs. Year, showing US (forecast) in green and US (actual) in blue from 1991 to 2000.
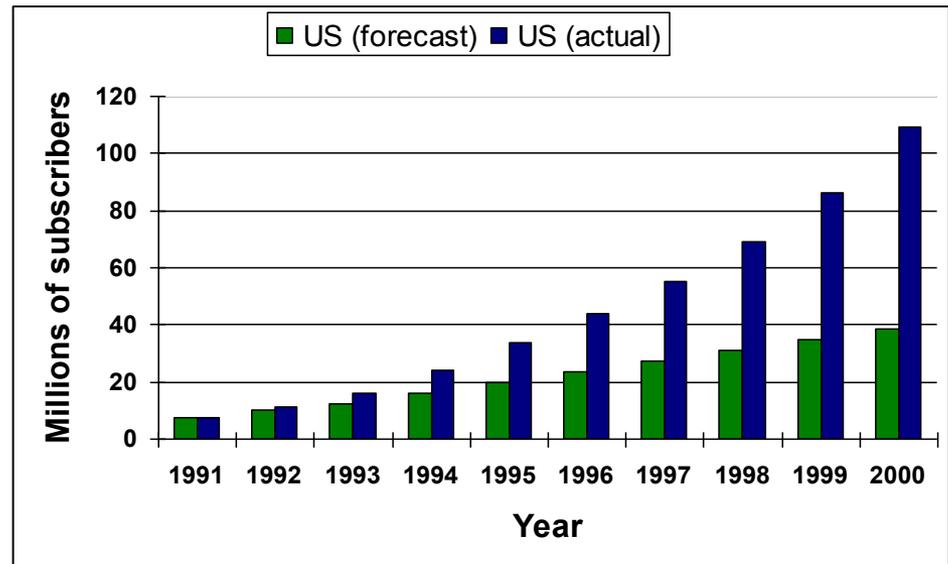
Lifecycle cost

$$CPF = \frac{I\left(1+\dfrac{k}{100}\right)^T + \displaystyle\sum_{i=1}^{T} C_{ops,i}}{\displaystyle\sum_{i=1}^{T} C_s \cdot 365 \cdot 24 \cdot 60 \cdot L_{f,i}}$$

Number of billable minutes

Cost per function [$/min]
Initial investment cost [$]
Yearly interest rate [%]
Yearly operations cost [$/y]
Global instant capacity [#ch]
Average load factor [0…1]
Number of subscribers
Average user activity [min/y]
Operational system life [y]

Numerical Example:

$I = 3 \ [\text{B\$}]$
$k = 5 \ [\%]$
$C_{ops} = 300 \ [\text{M\$/y}]$
$T = 15 \ [\text{y}]$

$C_s = 100{,}000 \ [\#\text{ch}]$
$N_u = 3 \cdot 10^6$
$A_u = 1{,}200 \ [\text{min/y}]$

$$\boxed{CPF = 0.20 \ [\$/\text{min}]}$$

$$L_f = \min \begin{cases} \dfrac{N_u \cdot A_u}{365 \cdot 24 \cdot 60 \cdot C_s} \\ 1.0 \end{cases}$$

But with $N_u = 50{,}000$
$\longrightarrow CPF = 12.02 \ [\$/\text{min}]$
Non-competitive

Design Space

Astro-dynamics
- Constellation Type: C
- Orbital Altitude: h
- Minimum Elevation Angle: e_{min}

Satellite Design
- Satellite Transmit Power: P_t
- Antenna Size: D_a
- Multiple Access Scheme MA:

Network
- Network Architecture: ISL

Polar, Walker	
500,1000,1500,2000	[km]
2.5,7.5,12.5	[deg]
200,400,800,1600,2400	[W]
1.0,2.0,3.0	[m]
MF-TDMA, MF-CDMA	[-]
yes, no	[-]

$$X_{1440} = \begin{pmatrix} \text{C: 'walker'} \\ \text{h: 2000} \\ \text{emin: 12.5000} \\ \text{Pt: 2400} \\ \text{DA: 3} \\ \text{MA: 'MFCD'} \\ \text{ISL: 0} \end{pmatrix}$$

This results in a <u>1440</u> full factorial, combinatorial co design space

Objective Vector (Output) J

- Performance (fixed)
  - Data Rate per Channel: R=4.8 [kbps]
  - Bit-Error Rate: $p_b=10^{-3}$
  - Link Fading Margin: 16 [dB]

- Capacity
  - C_s: Number of simultaneous duplex channels

- Cost
  - Lifecycle cost of the system (LCC [$]), includes:
    - Research, Development, Test and Evaluation (RDT&E)
    - Satellite Construction and Test
    - Launch and Orbital Insertion
    - Operations and Replenishment

Multidisciplinary Simulator Structure

Input Vector $\mathbf{x}$ Constants Vector $\mathbf{p}$

$h, \varepsilon_{\min}$

m_{sat}

Constellation

Spacecraft

m_{sat}

Launch Module

LV

Cost

T, p

n_{spot}

nGW

ISL

Satellite Network

Link Budget

R_s

Capacity

C_s

P_t, D_a, MA

LCC

m_{sat} Satellite Mass
T Number of Satellites
p Number of orbital planes

n_{spot} Number of spot beams
nGW Number of gateways
LV Launch vehicle selection

Output Vector $\mathbf{J}$
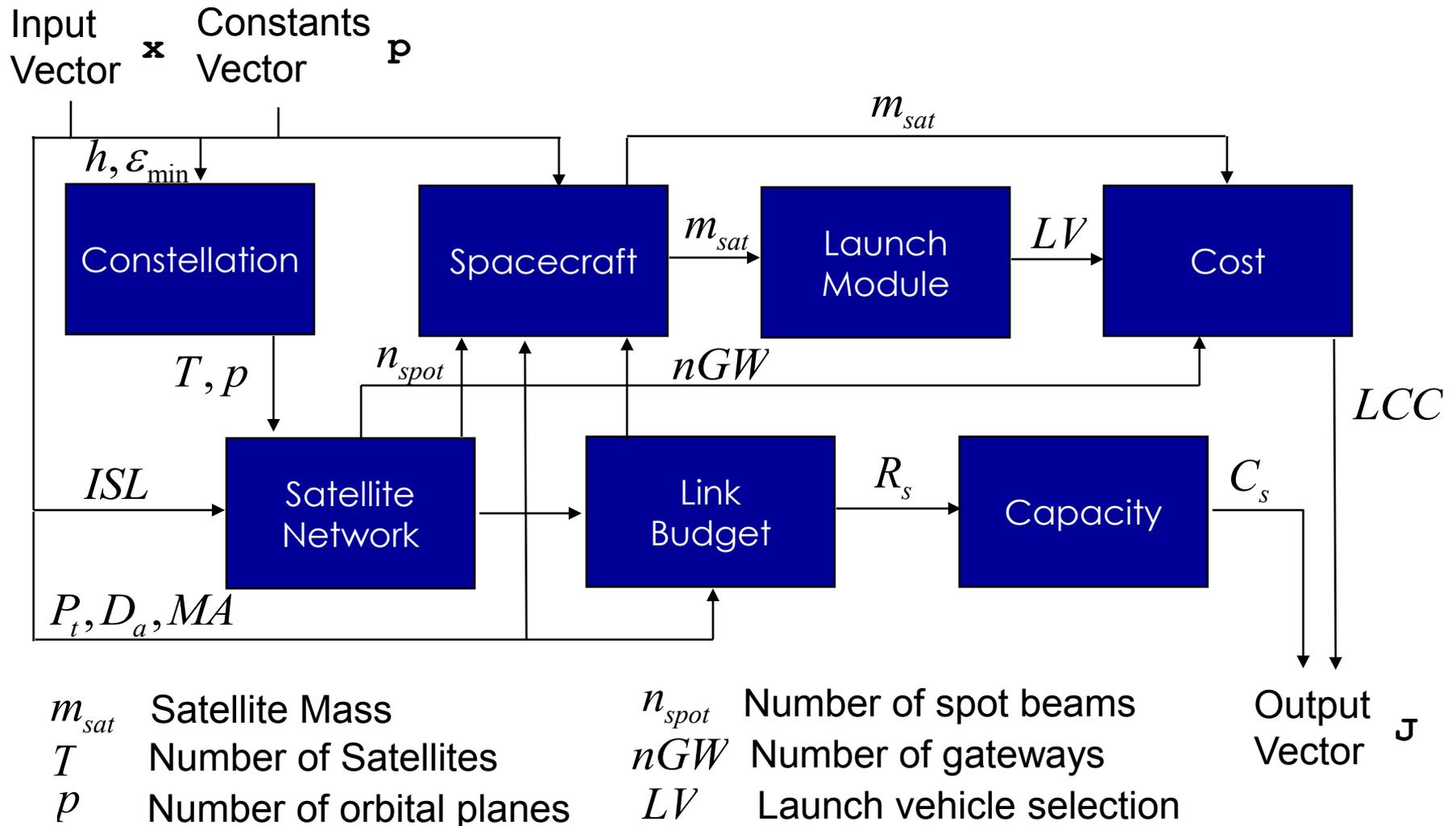
Note: Only partial input-output relationships shown

a) Physics-Based
   Models

Energy per bit
over noise ratio:

$$\frac{E_b}{N_0} = \frac{PG_rG_t}{kL_{space}L_{add.}T_{sys.}R}$$

(Link Budget)

b) Empirical
   Models

(Spacecraft)

Scaling models
derived from
FCC database

$$m_{sat} = 38\left(0.14P_t + m_{prop}\right)^{0.51}$$
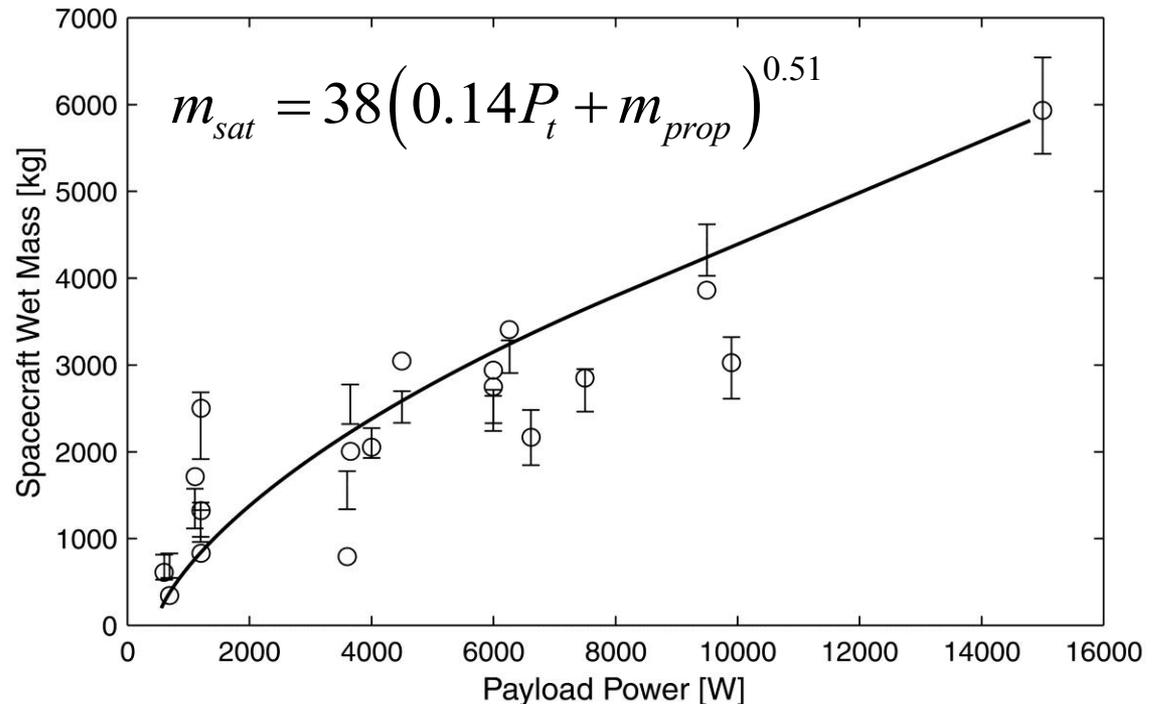
Springmann P.N., and de Weck, O.L. "A Parametric Scaling Model for Non-Geosynchronous Communications Satellites", *Journal of Spacecraft and Rockets***, May-June 2004**

Benchmarking

Benchmarking is the process of validating a simulation by comparing the predicted response against reality.
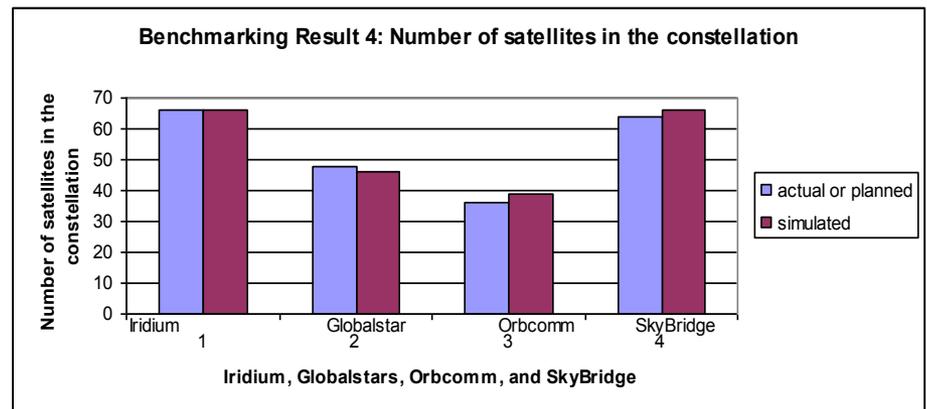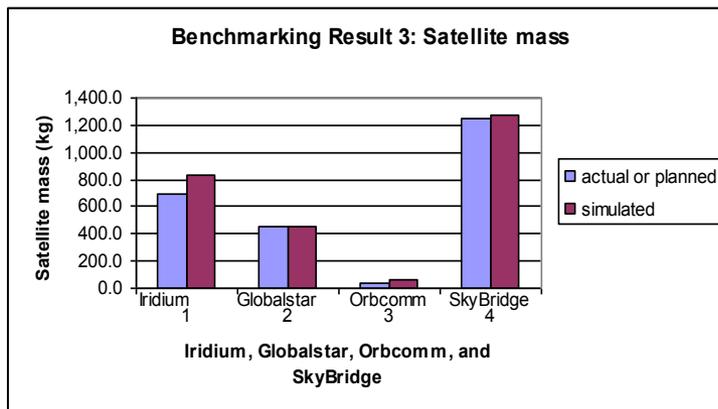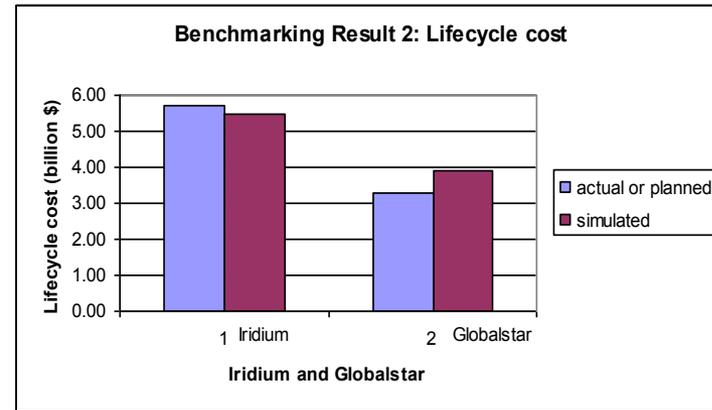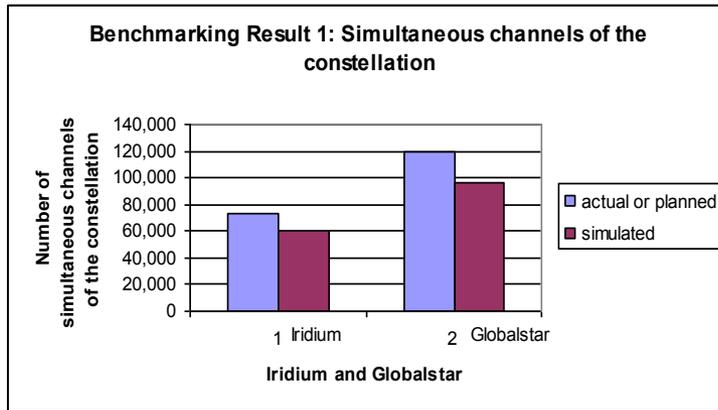
Traditional Systems Engineering

- The traditional approach for designing a system considers configurations (architectures) to be fixed over time.

- Designers look for a Pareto Optimal solution in the Trade Space given a targeted capacity.
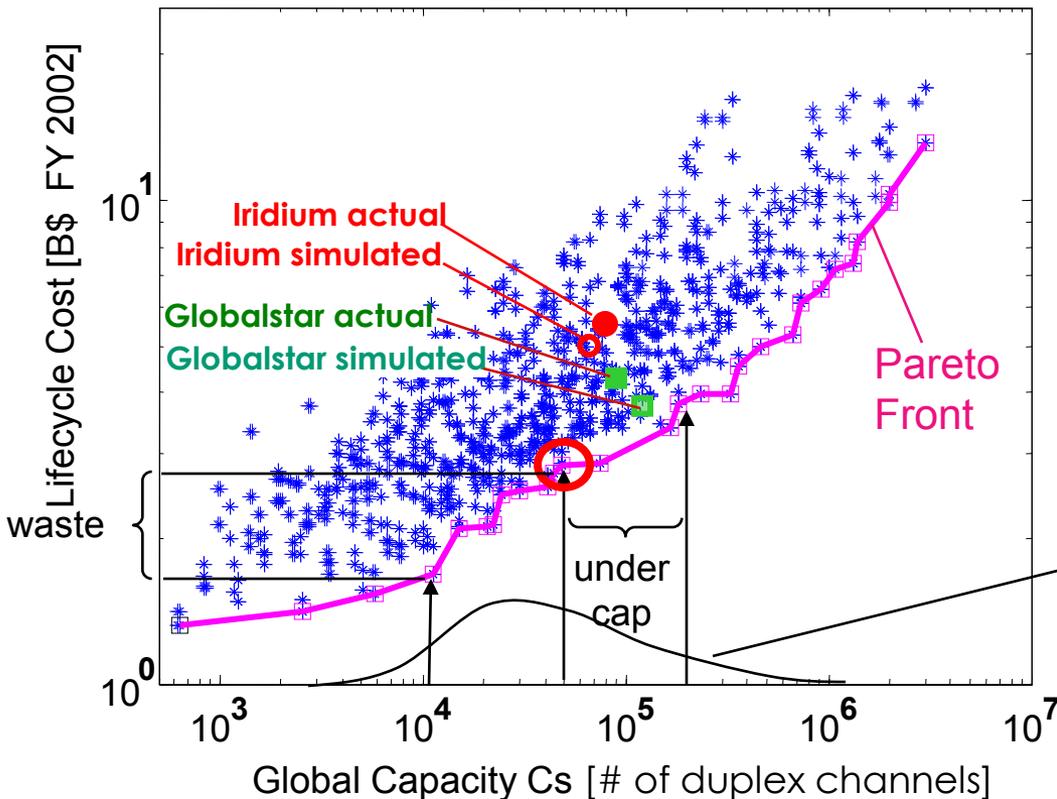
If actual demand is below capacity, there is a <u>waste</u>

If demand is over the capacity, <u>market opportunity</u> may be missed

Demand distribution Probability density function

$$P\{a < D \le b\} = \int_a^b f_D(\delta)\mathrm{d}D$$

$$0 \le f_D(D) \text{ for all } D$$

$$\int_{-\infty}^{\infty} f_D(\delta)\mathrm{d}D = 1$$

Lifecycle Cost [B\$ FY 2002]

Iridium actual
Iridium simulated
Globalstar actual
Globalstar simulated

Pareto Front

waste

under cap

10^1
10^0
10^3 10^4 10^5 10^6 10^7

Global Capacity Cs [# of duplex channels]

Staged Deployment

- Adapt to uncertain demand with a staged deployment strategy:

  - A smaller, more affordable system is initially built

  - This system has the flexibility to increase its capacity if demand is sufficient and if the decision makers can afford additional capacity

- **Economic Advantage**

  - Some capital investments are deferred to later

  - The ability to reconfigure and deploy the next stage is a real option

$\mathbf{x_{flexible}}$

Astro-dynamics

Constellation Type: C

Orbital Altitude: h

Minimum Elevation Angle: ε_{min}

$\mathbf{x_{base}}$

Satellite Design

Satellite Transmit Power: P_t

Antenna Size: D_a

Network

Multiple Access Scheme MA:

Network Architecture: ISL

Rationale:
Keep satellites the same and change only arrangement in space
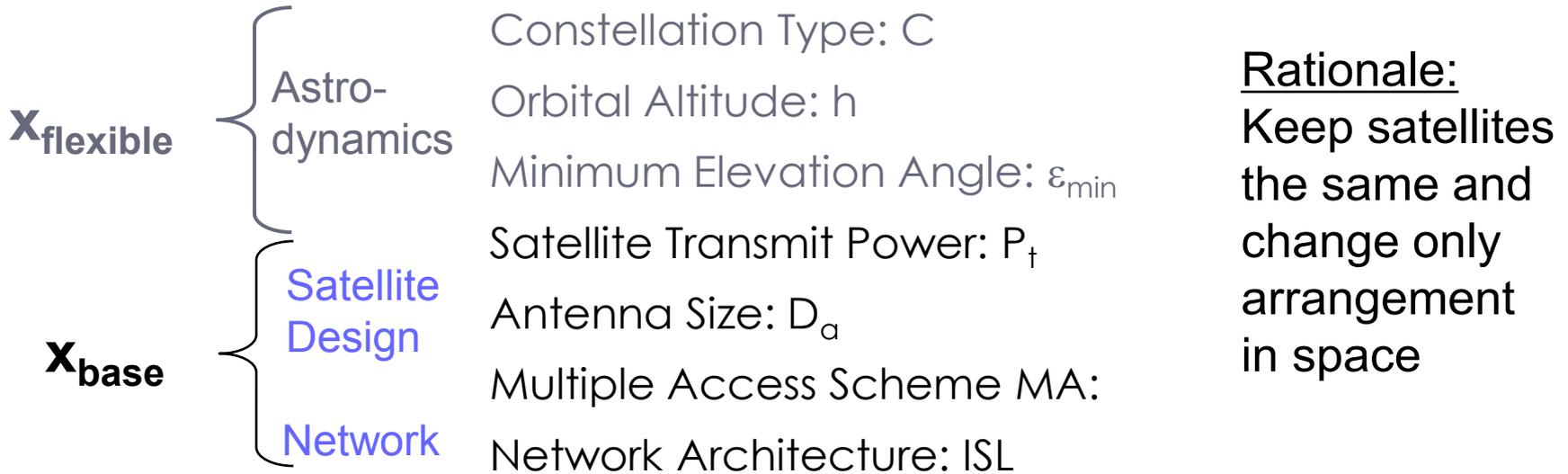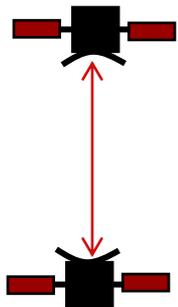
Stage I

```
    C: 'walker'
    h: 2000
 emin: 12.5000
   Pt: 200 W
   DA: 1.5 m
   MA: 'MFCD'
  ISL: 1=yes
```

Stage II
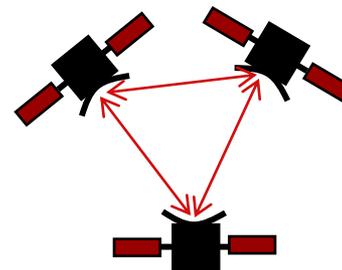
```
    C: 'polar'
    h: 1000
 emin: 7.5000
   Pt: 200 W
   DA: 1.5 m
   MA: 'MFCD'
  ISL: 1=yes
```

$\mathbf{x^I_{base}} = \mathbf{x^{II}_{base}}$

family

h= 400 km
ε= 35 deg
N_{sats}=1215

h= 400 km
ε= 20 deg
N_{sats}=416

h= 2000 km
ε= 5 deg
N_{sats}=24

h= 800 km
ε= 5 deg
N_{sats}=54

h= 400 km
ε= 5 deg
N_{sats}=112

Lifecycle cost [B$]

System capacity
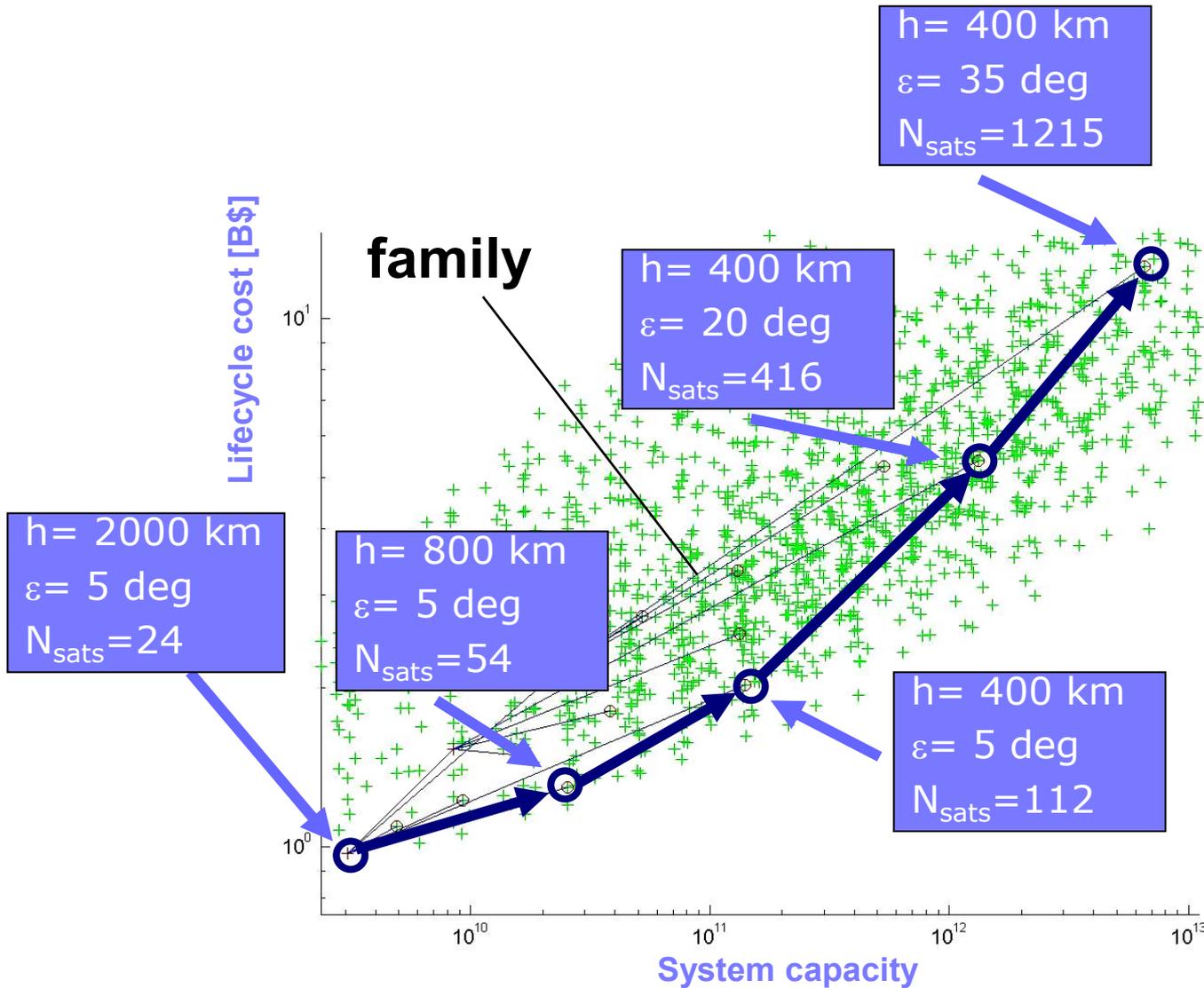
Constant:

Pt=200 W

DA=1.5 m

ISL= Yes

Total: 40 Paths

$$\frac{\Delta D}{D} = \mu \Delta t + \sigma \varepsilon \sqrt{\Delta t}$$

D - demand
Δt – time period
ε- SND random variable
μ, σ - constants

$$E\left[\frac{\Delta D}{D}\right] = \mu \Delta t$$

$$\mathrm{var}\left[\frac{\Delta D}{D}\right] = \sigma^2 \Delta t$$

x 10^5

Geometric Brownian Motion Model

GBM model, Δt = 1 month,
D_o = 50,000, μ = 8% p.a., σ = 40% p.a.
− 3 scenarios are shown

Demand [N$_{users}$]

Time [years]
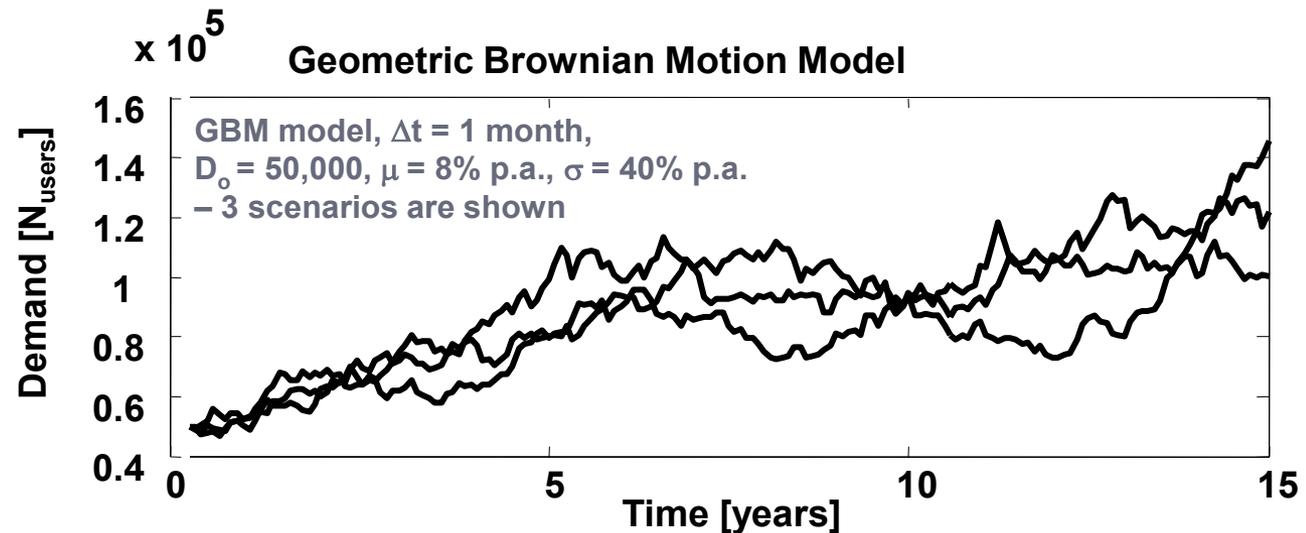
- Demand can go up or down between two decision points
- Infinitely many scenarios can be generated based on this model

$$u = e^{\sigma\sqrt{\Delta t}}$$

$$d = 1/u$$

$$p = \frac{e^{u\Delta t} - d}{u - d}$$

Discretized
Random
Walk

Binomial tree for Demand

Demand [nb of subscribers]

Time [years]

p

1-p
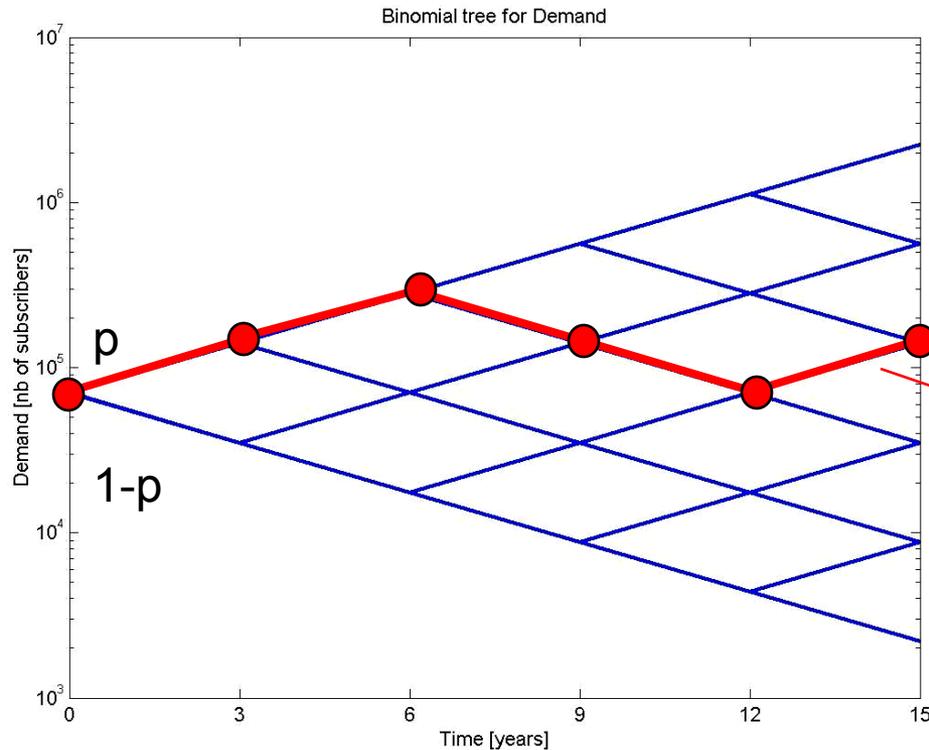
Total

2^5=32
scenarios

Sample
scenario

$$P(i) = p^k \left(1 - p\right)^{n-k}$$

Step 4: Calculate cost of paths

- We compute the costs of a path with respect to each demand scenario

- We then look at the weighted average of every allowable path for cost over all scenarios

- Decision rule: We always adapt to demand when demand exceeds capacity

- The costs are discounted: the present value of LCC is considered

Cap_2

Cap_1

Demand [nb of subscribers]

Costs

wait **Deploy** wait wait

Initial deployment

2nd stage

Best Path

LCC of rigid design

Traditional design

E[ΔLCC]=$650 million
value of real option

E [LCC(path_j)*]= Best Deployment Strategy

- For a given targeted capacity, we compare our solution to the traditional approach
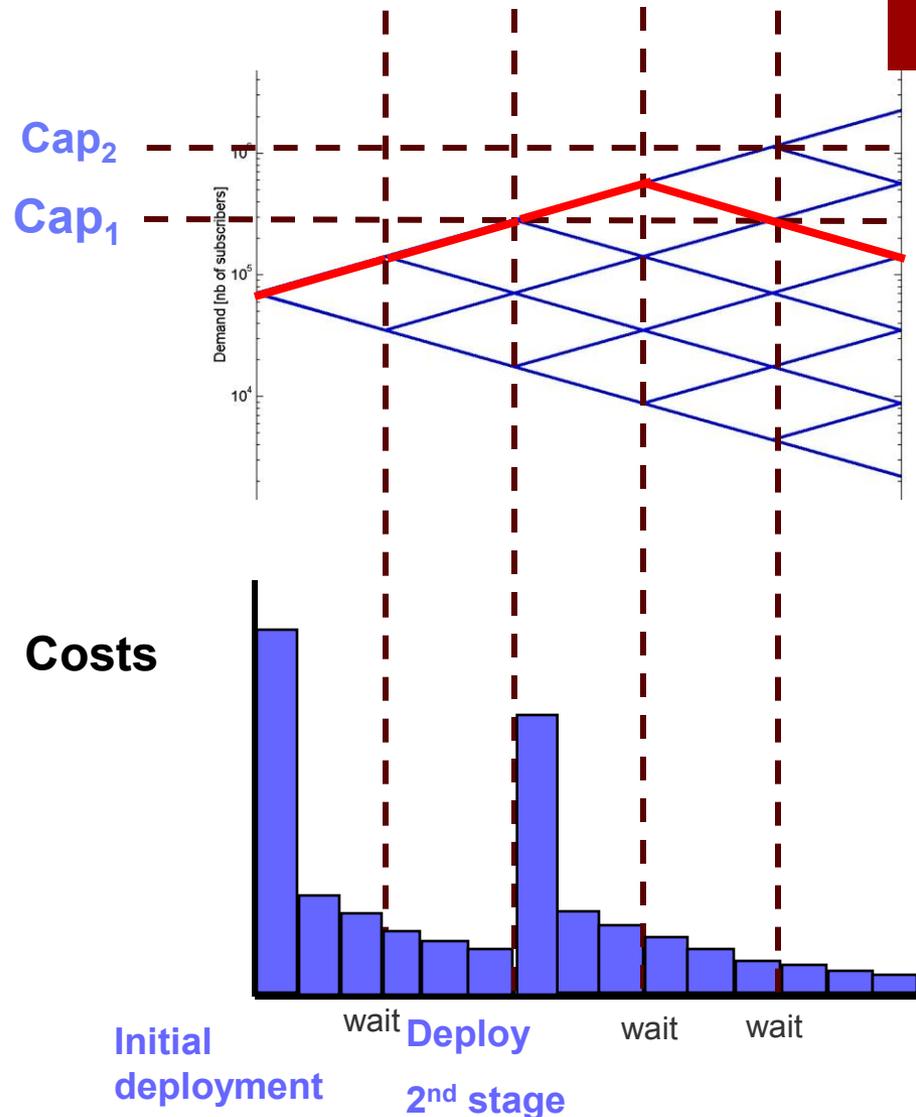
- Our approach allows large savings (30% on average)
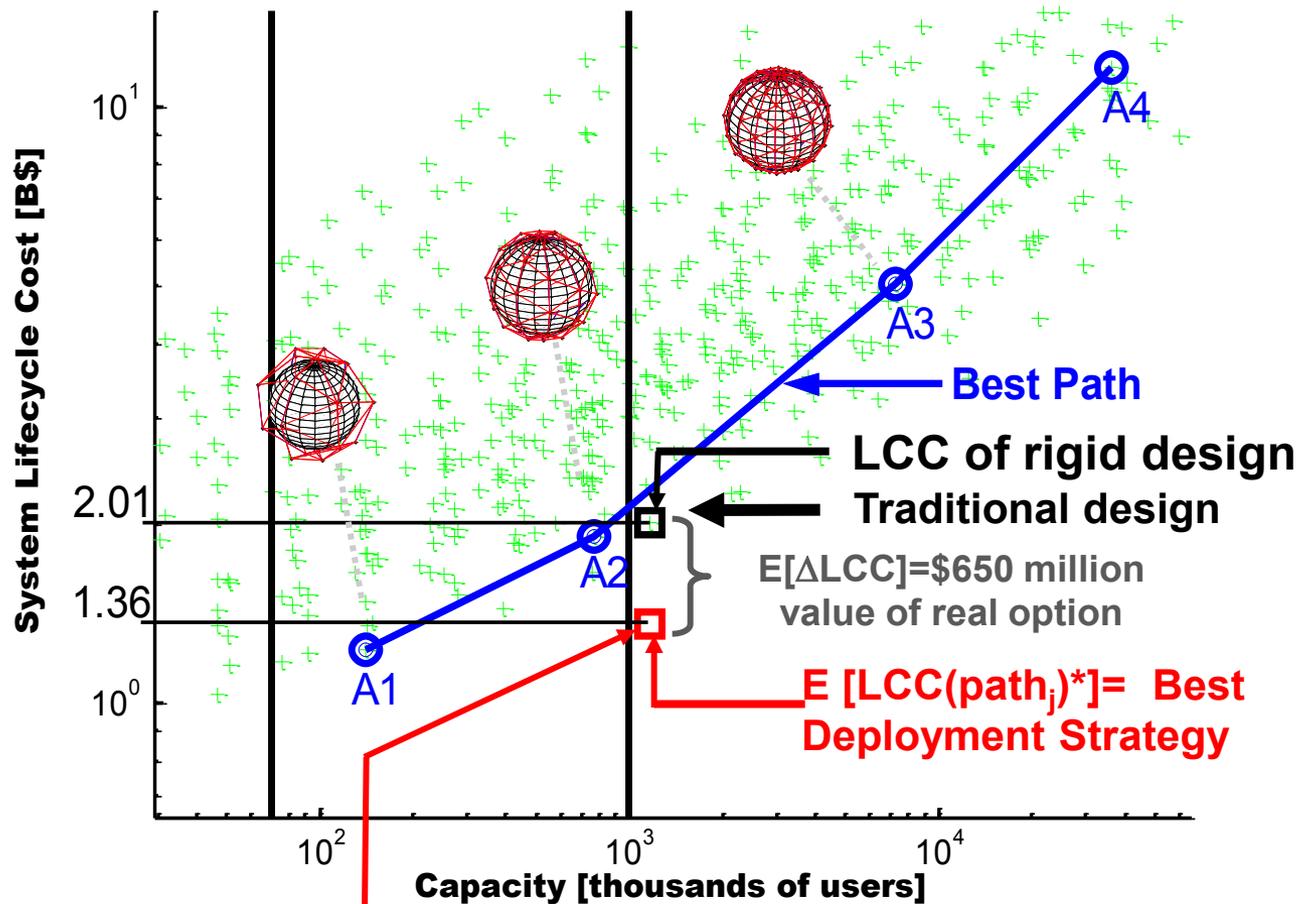
$$E\left[LCC(path_j)\right] = \sum_{i=1}^{n} p_i LCC\left(scenario^i_{path_j}\right)$$

Outline for Today

- Definition of Lifecycle Management

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- A Case Study
  - Reconfiguration of Communications Satellite Constellations

- Summary of Key Concepts taught in this class

- Career / Study Recommendations regarding SE

Learning Objectives Revisited

Participants in this class will be able to …

- SE1: Describe the most important **Systems Engineering standards and best practices** as well as newly emerging approaches[1]

- SE2: Structure the **key steps in the systems engineering process** starting with stakeholder analysis and ending with transitioning systems to operations

- SE3: Analyze the **important role of humans** as beneficiaries, designers, operators and maintainers of aerospace and other systems

- SE4: Characterize the **limitations of the way that current systems engineering is** practiced in terms of dealing with complexity, lifecycle uncertainty and other factors

- SE5**: Apply some of the fundamental methods and tools** of systems engineering to a 'simple' cyber-electro-mechanical system as a stepping stone to more complex and real world projects

[1] Our main "textbook" for the class will be the NASA Systems Engineering Handbook, NASA/TP-2007-6105, Rev 1. All participants will receive a copy of the handbook.

Note: This class is not an explicit preparation for CSEP Certification

SE1: Standards and Handbooks
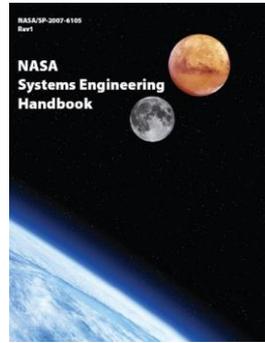
■ Systems Engineering Standards

1. **NASA Systems Engineering Handbook,** NASA/SP-2007-6105, Rev 1, Dec 2007

2. **INCOSE Systems Engineering Handbook**, A Guide for System Lifecycle Processes and Activities, INCOSE-TP-2003-002-03, version 3, International Council on Systems Engineering (INCOSE), June 2006 – version 4 was just issued in July 2015

3. **ISO/IEC 15288:2008(E), IEEE Std 15288-2008**, Second edition, 2008-02-01 Systems and software engineering — System life cycle processes, Ingénierie des systèmes et du logiciel — Processus du cycle de vie du système – May 2015 edition

4. **ECSS-E-10A** – European Systems Engineering Standard, http://www.ecss.nl/

■ Selected Conference and Journal Articles (in "Readings" folder)
  ■ Explore beyond traditional SE
  ■ Somewhat MIT-centric

What is your opinion about these standards now, at the end of the class?

See the question in supplement files.

Numbers indicate the session # in this class

SE4: Stakeholders and Value Network

Legend:
- → Political (red)
- → Information (purple)
- → Goods/Service (blue)
- → Financial (green)

- Market Stakeholders
- Nonmarket Stakeholders
- The Focal Organization
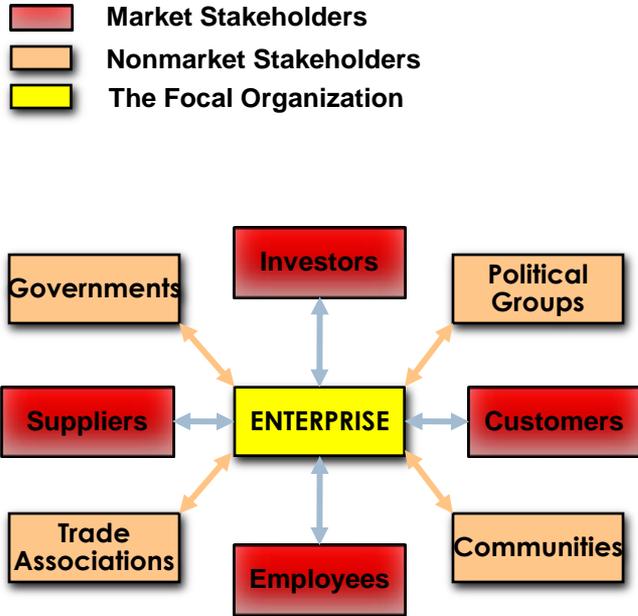
"Hub-and-Spoke" Stakeholder Model
(Adapted from Donaldson and Preston, 1995)

Hub-and-spoke diagram nodes: Governments, Investors, Political Groups, Suppliers, ENTERPRISE, Customers, Trade Associations, Employees, Communities

Stakeholder Value Network diagram nodes and flows: Future Project Approval, Federal Support, Project Lobbying, Regulatory Approval, Local Community, Host-Country Government, Economic Support, Investors, Workforce, Employment, Project Approval, Investment, RO, Environmental Compliance, Taxes, Political Influence, High-grade Goods, Logistical Support, ENTERPRISE, Project, Host-Country Corporation, Low-grade Goods, Revenue Sharing, Investment, Technology Transfer, Technology, Technology Reqts, Environmental Impact Plan, Policy Support, NGO, Product, Sales Revenue, Product Subsystems, Contracts, Consumers, Suppliers

**Stakeholder Value Network
(Feng, Cameron, and Crawley, 2008)**

Figure 3 in Wen Feng; Edward F. Crawley; Olivier de Weck; Rene Keller;Bob Robinson. : Dependency structure matrix modelling forstakeholder value networks". Proceedings of the 12thInternational DSM Conference, Cambridge, UK, 22.-23.07. 3-16.DSM 2010. CC by-nc-sa 3.0

SE4: Stakeholder Value Network (SVN) Methodology

Inputs/Outputs　　　　　**Steps**　　　　　**Techniques**

Stakeholders and Their Roles, Objectives, and Needs

Qualitative Model of Stakeholder Value Network

Quantitative Model of Stakeholder Value Network

The Solution Space of Value Paths between Any Two Stakeholders

Important Paths/Outputs/Stakeholders/Flows

Step 1: Mapping

Step 2: Quantifying

Step 3: Searching

Step 4: Analyzing

Document Survey, Stakeholder Interview, and Network Visualization

Questionnaire for Value Flow Scoring (Intensity, Importance, and Timing)

Object-Process Network (OPN) or Matrix Multiplication

Network Measurements Definition and Network Statistics Construction

Feng W., Crawley E.F., de Weck O.L., Keller R., Robinson R., "Dependency Structure Matrix Modeling for Stakeholder Value Networks", 12th International Dependency and Structure Modeling Conference, DSM'10, Cambridge, UK, 22-23 July 2010

SE3: Role of individuals in SE: **Human Factors**

- How to design systems so that humans can use them effectively and safely (interfaces, procedures …)

- Often ignored until too late

- Result of classical SE (without human factors):

Important Human Factors Questions
How to best display status information?
Human tasks during operations?
Level of automation?
Training requirements for operators?

Russian Nuclear Power Plant Control Room (Source: Prof. M. Cummings)

Courtesy of Alexey Danichev on Wikipedia. cc: by-nc-sa.

A simplified Human Systems Engineering (HSE) Process
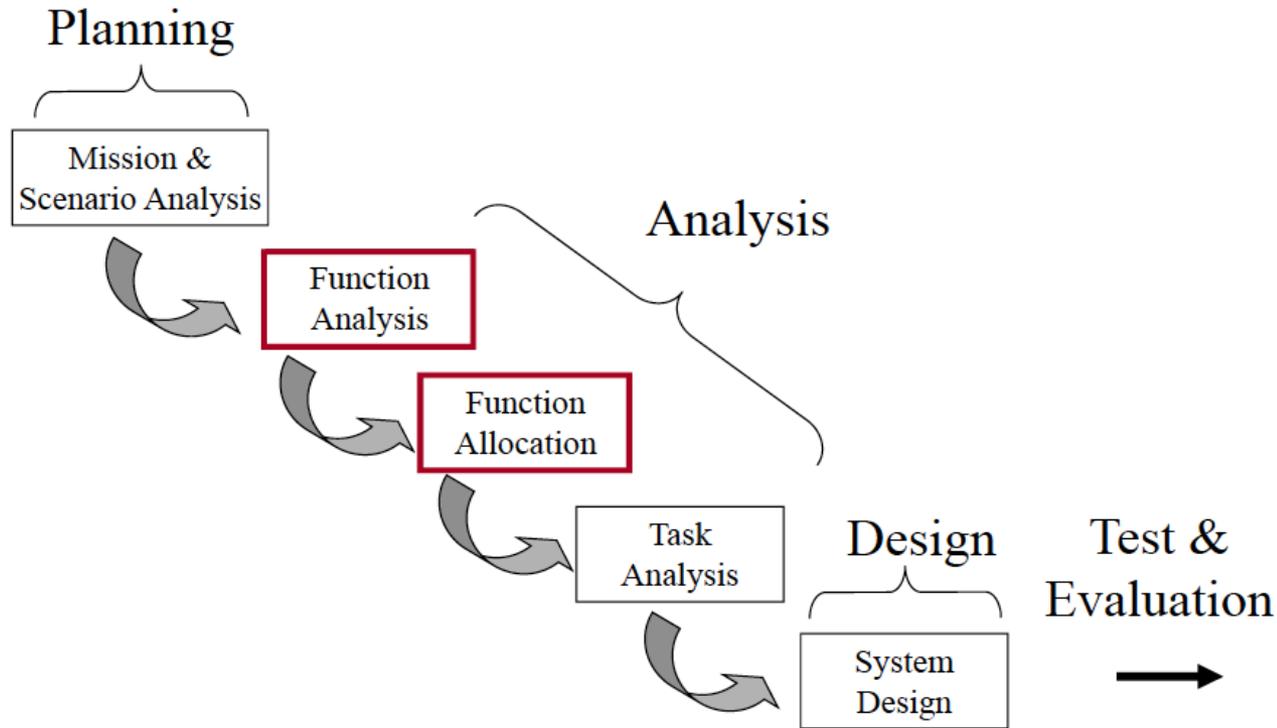
Courtesy of Mary Cummings. Used with permission.

- Credit: Prof. Missy Cummings
  - More info at MIT: 16.470J Statistical Methods in Experimental Design
  - Now taught by DR. Carr

Function Allocation is crucial

- Growing system complexity and mission requirements mean that mutually exclusive role allocation between humans and automation will not be sufficient

- Humans and automation both have strengths & limitations
    - Brittleness vs. attention inefficiencies

Human Performance Curve
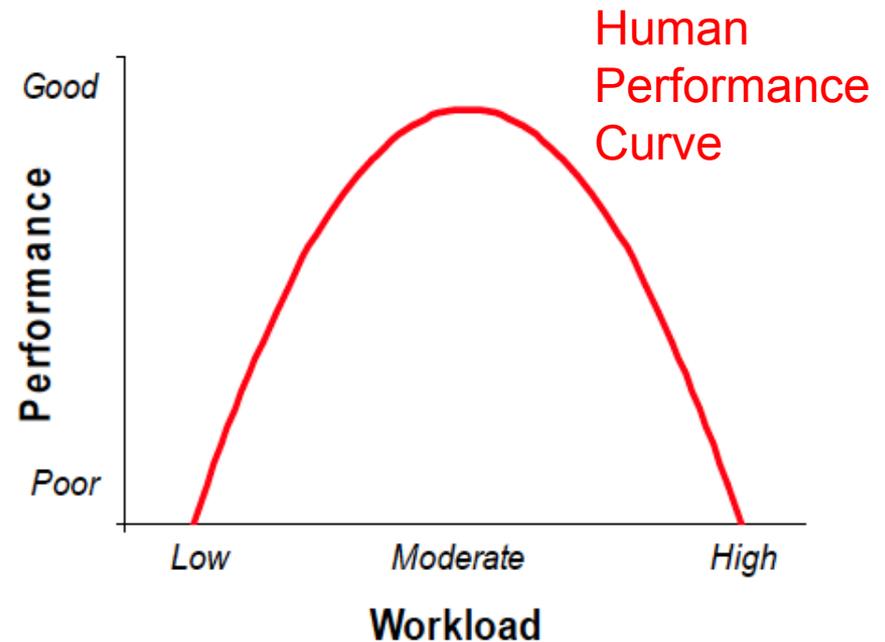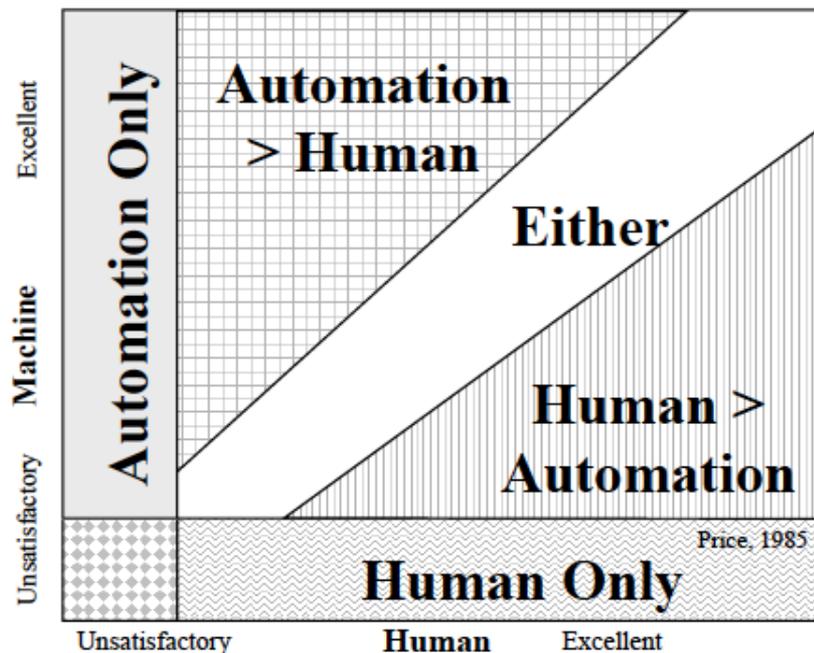
SE4: System Complexity

Magic Number 7 +/-2 [Miller 1956]

http://www.musanim.com/miller1956/

Limitations of human mind at Levels 3+

How many levels in drawing tree?

$$\#levels = \left\lceil \frac{\log(\# \, parts)}{\log(7)} \right\rceil$$

		~ #parts	#levels	
■ Screwdriver	(B&D)	3	1	simple
■ Roller Blades	(Bauer)	30	2	
■ Inkjet Printer	(HP)	300	3	
■ Copy Machine	(Xerox)	2,000	4	
■ Automobile	(GM)	10,000	5	
■ Airliner	(Boeing)	100,000	6	complex

Source: Ulrich, K.T., Eppinger S.D. , Product Design and Development
Second Edition, McGraw Hill, 2nd edition, 2000, Exhibit 1-3

Get th

Component Iss
Months

by Peter B. de Selding — Oct

In a conference call with investors, Iridium Chief Executive Matthew J. Desch made no attempt to hide his exasperation at the latest delay, especially because it was caused by a component that had posed issues for prime contractor Thales Alenia Space previously.

The component, built by ViaSat Inc. of Carlsbad, California, is an extension of a Ka-band transmit/receive module. This hardware already had been associated with production delays on Iridium Next.

"Thales now appears to have found an issue during post-assembly testing of this same T/R module," Desch said. The defect "could create performance problems in the Ka-band downlink to our Earth stations."

Thales Alenia Space of France and Italy will now change the circuitry in the module and then reinstall it onto the first two satellites to launch on Dnepr.

"This is particularly frustrating in that it should have been caught and resolved much earlier in development," Desch said. "In light of previous program delays, Thales Alenia knows — quite clearly — my disappointment."

-Mars Plans
Lack Details

Today

CHINA SATCOM

Rich Satellite Resources,
Vast Market Potential.

click here

Most Read

1. Blue Origin may have New Shepard, but SpaceX has Karlie Kloss

"This is particularly frustrating in that it should have been caught and resolved much earlier in development," Iridium Chief Executive Matthew J. Desch said. "In light of previous program delays, Thales Alenia knows — quite clearly — my disappointment." Credit: Iridium

SE5: Application to a case case

- Cansat 2016 Competition served as our "safe" case study
  - Clear rules, 47 requirements as a starter, cyber-physical complexity somewhere between levels 2 and 3, real stakeholders etc…

- **Comments about PDR**
  - All teams successfully passed PDR
    - Couple of RIDs issued, e.g. over-mass budget 500 grams, need to work out aerodynamics of advanced glider concepts etc…
  - Excellent application of SE concepts, some went beyond expectations
  - Importance of concept generation* and selection was very clear
  - Application Deadline was November 30, 2015

EPFL Team 4
SKALE
*Bio-Inspired Design
alsomitra macrocarpa*

200-300 mg

© W.P. Armstrong 2007
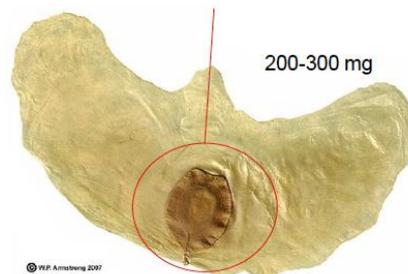
http://waynesword.palomar.edu/plfeb99.htm
Alsomitra shape → Roll and yaw stabilization

MIT Team 7
Glidestar
Rogallo Wing
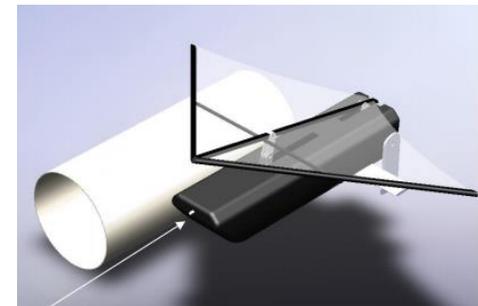
* Joint use of structured and unstructured creativity techniques: e.g. brainstorming -> morph

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Career / Study Recommendations for SE

- **Academic**
  - This class 16.842 / ENG-421 was just a "door opener" to systems engineering
  - Take classes that go deeper into individual topics, e.g. MBSE, System Safety, Multidisciplinary System Optimization (16.888/ESD.77 Spring 2016) etc…
  - Self-Study: SE Journal, IEEE Journals, etc…
  - Professional Degrees in Systems Engineering, e.g. MIT SDM (average age 33)

- **Professional**
  - Get experience on actual projects, e.g. MIT REXIS, EPFL CleanSpace One, Octanis 1, Solar Impulse etc.…
  - Start your own company / venture → It's a Systems Challenge

- INCOSE
  - Join as a student or professional member if interested
  - Certification as ASEP or CSEP ("Certified Systems Engineering Professional")

- Keep in Touch !

Thank you !

Students at MIT and EPFL
TAs: Ioana and Lise-Loup
MIT and EPFL Technical Staff
Prof. Volker Gass

Next Week: Voluntary Seminar on the Future of SE and Manufacturing

16.842 Fundamentals of Systems Engineering
Fall 2015