Systems Engineering:
Journey from Adolescence to Adulthood (1991-2016)

SWISSED16
The Swiss Society of Systems Engineering Day
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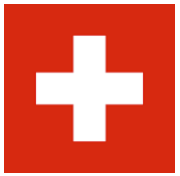
Adjunct Professor *EPFL* Space Center

Massachusetts Institute of Technology

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

What is special about 1991?



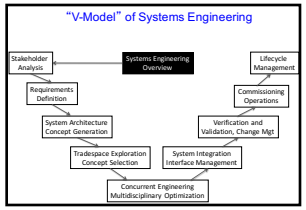
Switzerland celebrated its 700th Birthday !

I graduated from ETH Zurich – Dept. IIIE
"Betriebs- und Produktionswissenschaften"

Switzerland planned to procure the F/A-18 Military Aircraft from the U.S. Navy / McAir

INCOSE
International Council on Systems Engineering

The International Council for Systems Engineering (INCOSE) was founded



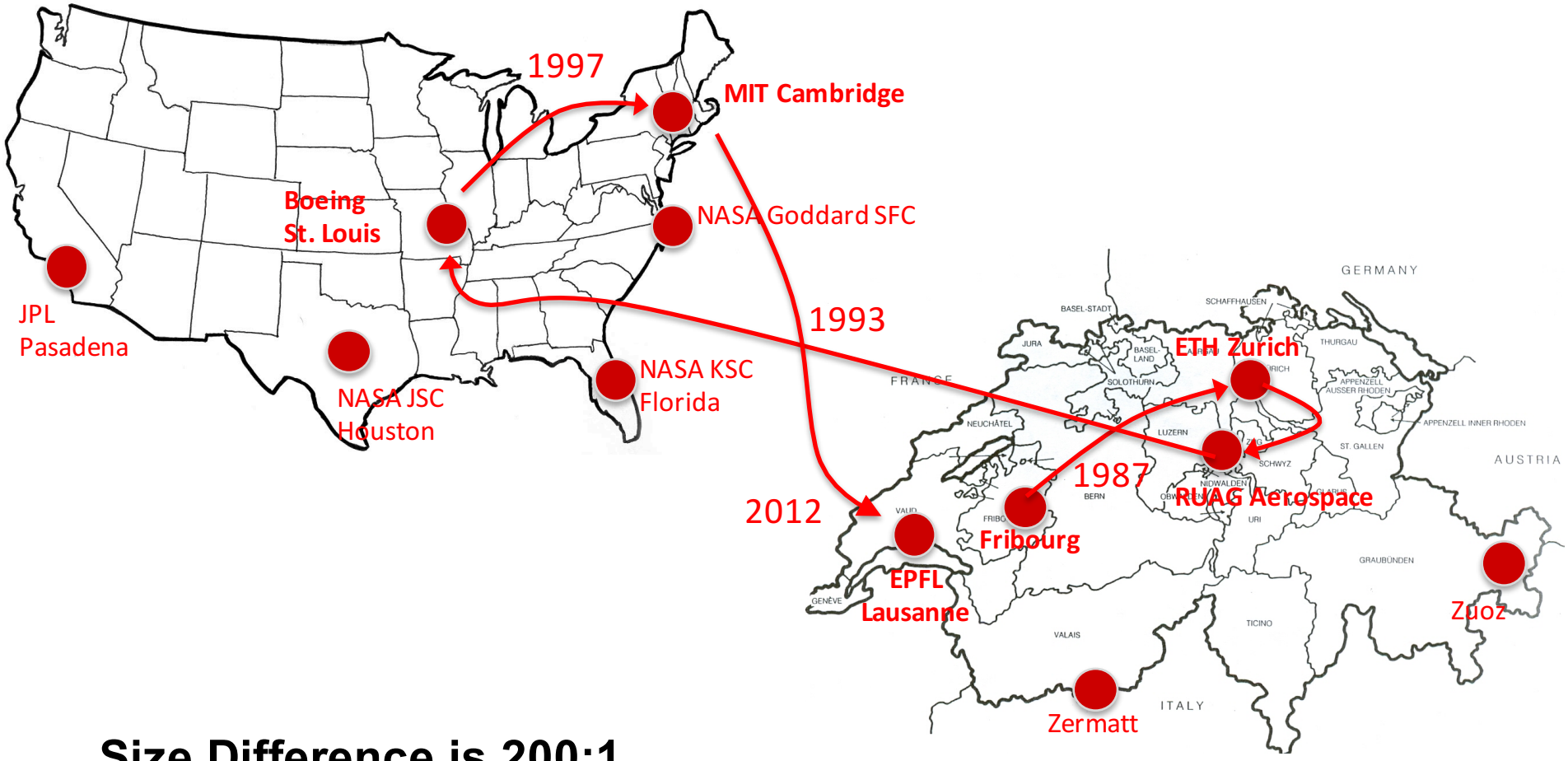
The now famous "V"-Model was published

Is Systems Engineering any further along today ?

Outline of this seminar

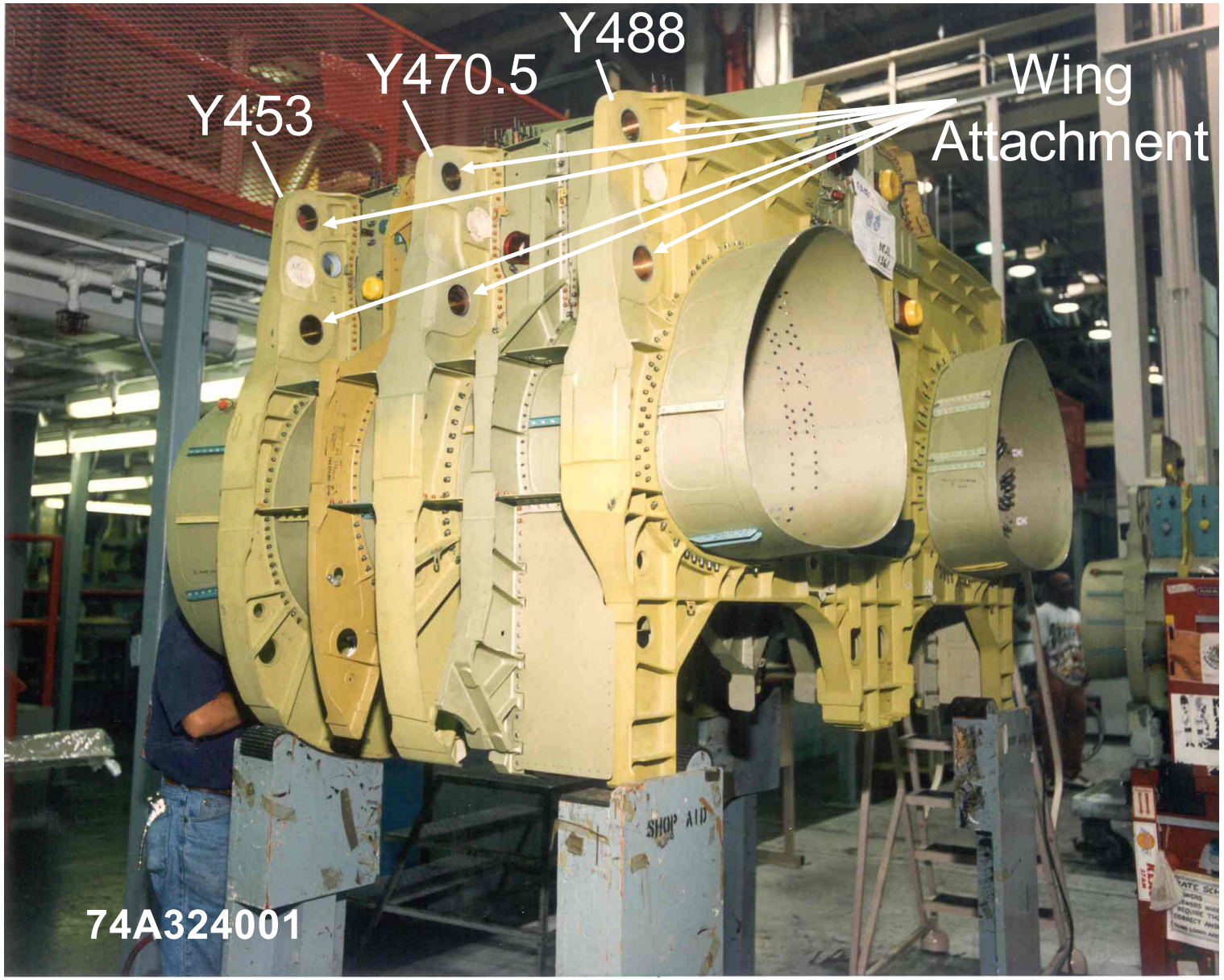
- The Swiss F/A-18 Story
- Research in Change Propagation Analysis
- META and Model-Based-Systems-Engineering (MBSE)
- “Utopia” for Systems Engineering in 2041

A Transatlantic Journey …



Size Difference is 200:1

F/A-18 Center Barrel Section



Swiss F/A-18 Experience

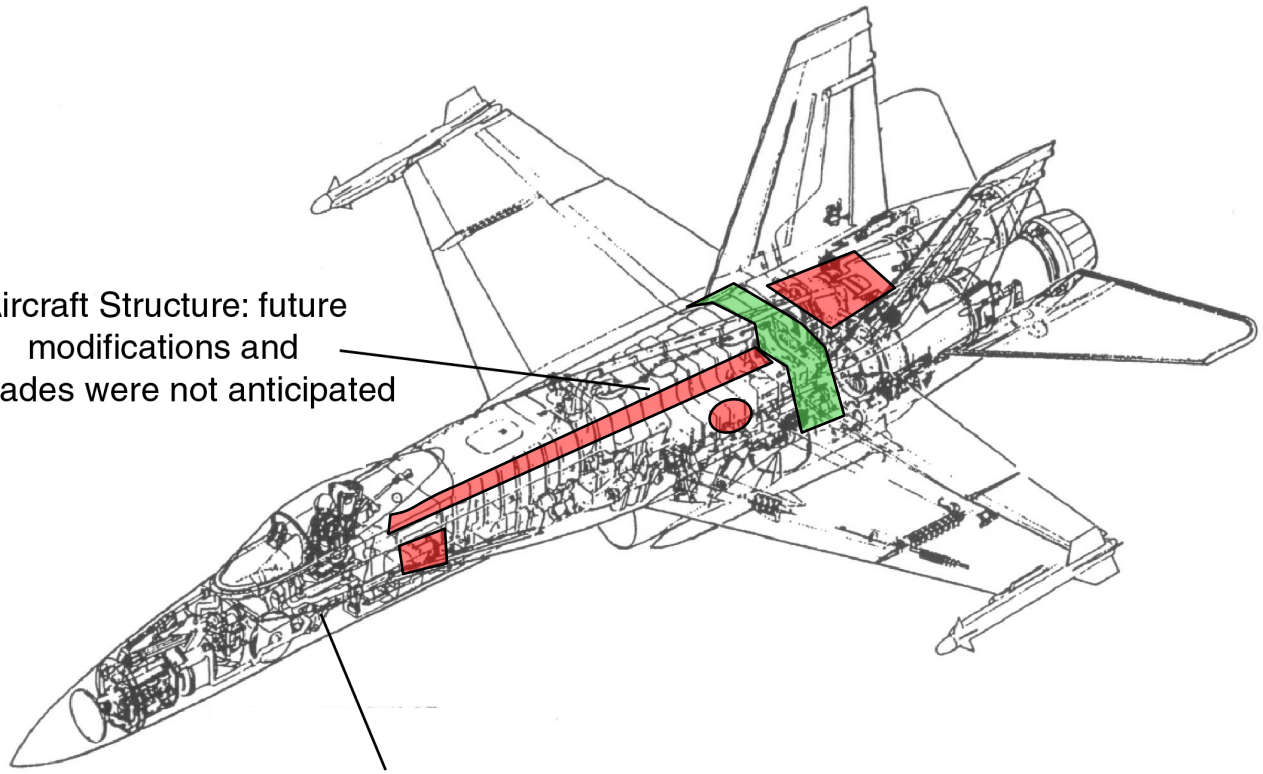


Fig.1: F/A-18 Aircraft

Multidisciplinary systems like aircraft are very complex and highly coupled

Typically optimized for mission performance

Difficult to change design when requirements change during lifecycle

Instigated changes
Propagated changes

Issue of Engineering Changes is critical:
- some were anticipated (avionics, software)
- others were not (structural airframe)
- F/A-18 C/D system was redesigned for a mission that was not part of the original set of requirements for the U.S. Navy

F/A-18 Lessons Learned

- Changes increased cost per aircraft by O(~$10M)
  - Encountered some "surprises" along the way
- Changing a system (or product) after its initial design is
  - often required to accommodate new requirements
  - expensive, and time-consuming if change was not anticipated in the original design → How "flexible" is the design?
- Change propagation
  - some changes are local and remain local
  - other changes start local, but propagate through the system in complex, unanticipated ways
- Can we predict why changes are initiated and how they propagate?

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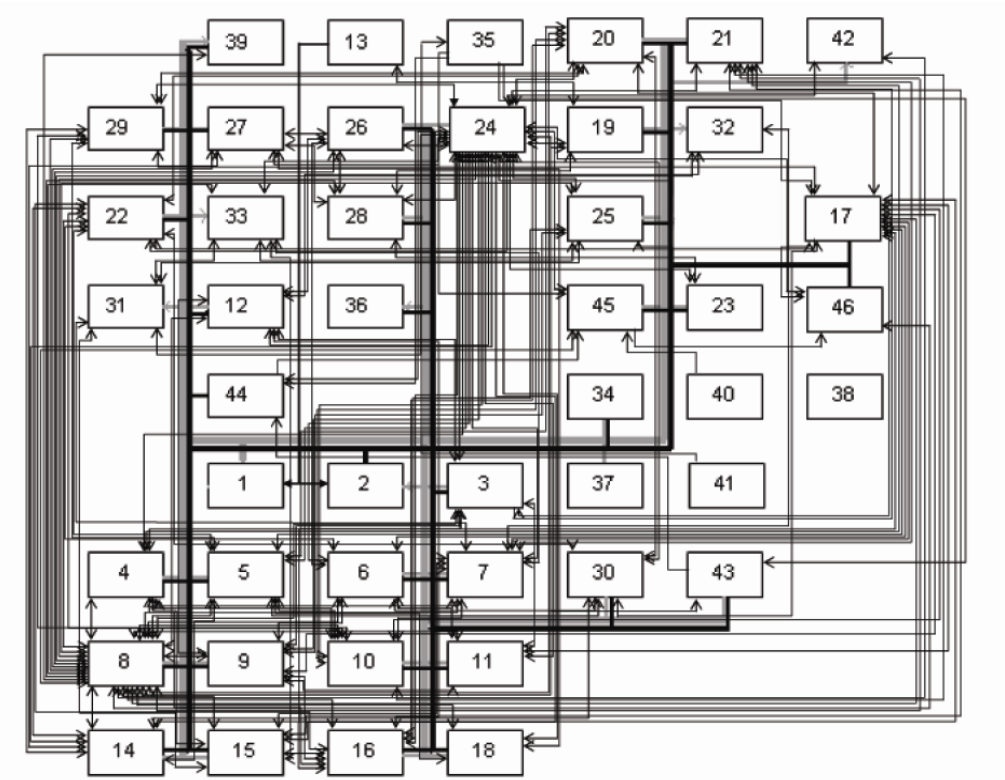
Change Propagation Analysis in Complex Systems

- Complex Sensor System
  - Long range sensor system, complex hardware, software, human operators
  - Derivative of earlier generation
  - 8 Year development program
- 46 Areas
  - Hardware
  - Software
  - Program Documentation
- System Map (graph)
  - Interconnections between areas



collaboration with

Raytheon

Giffin M., de Weck O., Bounova G., Keller R., Eckert C., Clarkson P.J., "Change Propagation Analysis in Complex Technical Systems", *Journal of Mechanical Design*, 131 (8), 081010, August 2009

Structure of the Data Set

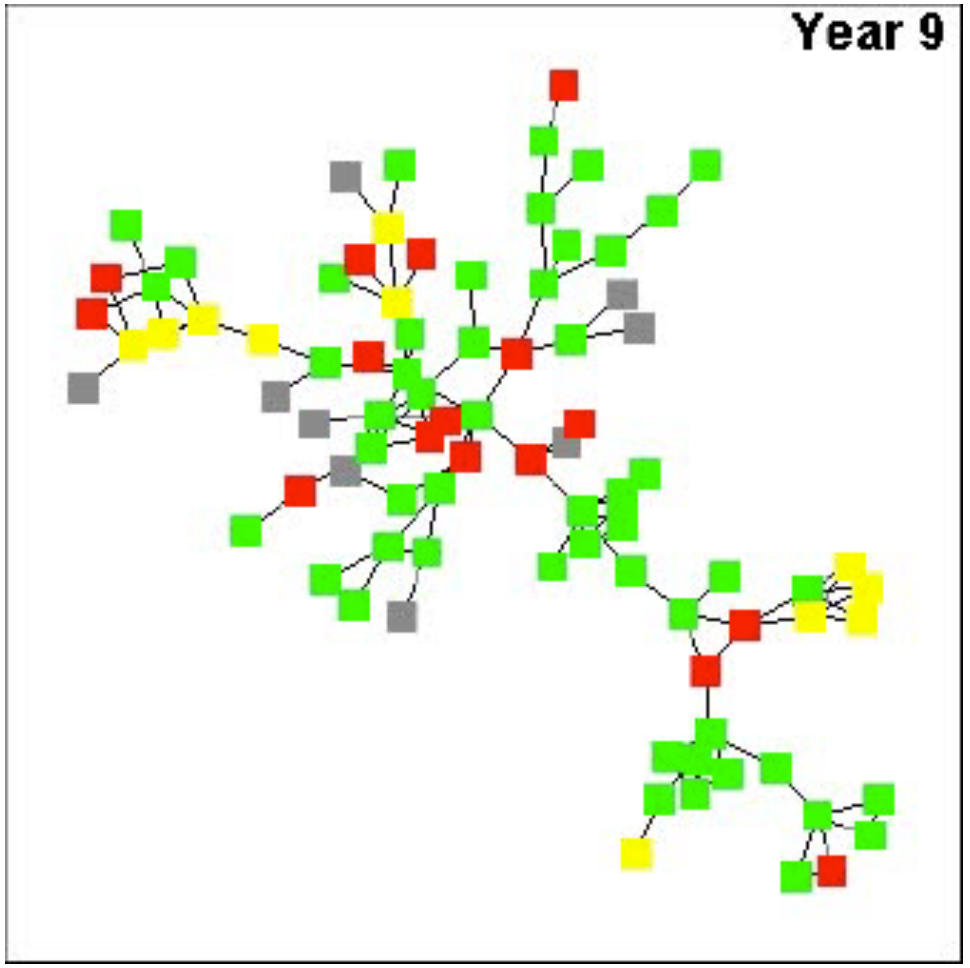
- Change Request Database
  - technical, managerial, procedural
  - track parent, child, siblings by areas with unique ID number
  - chronologically numbered IDs
  - Total of 41,500 change requests
- Data Mining Procedure
  - Export from DBMS to text file
  - Written into MySQL database with Perl scripts
  - Equivalent to a MS Word document with 120,000 pages
  - Sorting, Filtering, Anonymizing
  - Write simplified change request format (see right side)

Typical Change Request

ID Number	12345
Date Created Date Last Updated	06-MAR-Y5 10-JAN-Y6
Area Affected	19
Change Magnitude	3
Parent ID	8648
Children ID(s)	15678, 16789
Sibling ID(s)	9728
Submitter	eng231
Assignees	eng008 eng231 eng018
Associated Individuals	Admin_001 Engineer_271
Stage Originated, Defect Reason	[blank], [blank]
Severity	[blank]
Completed?	1

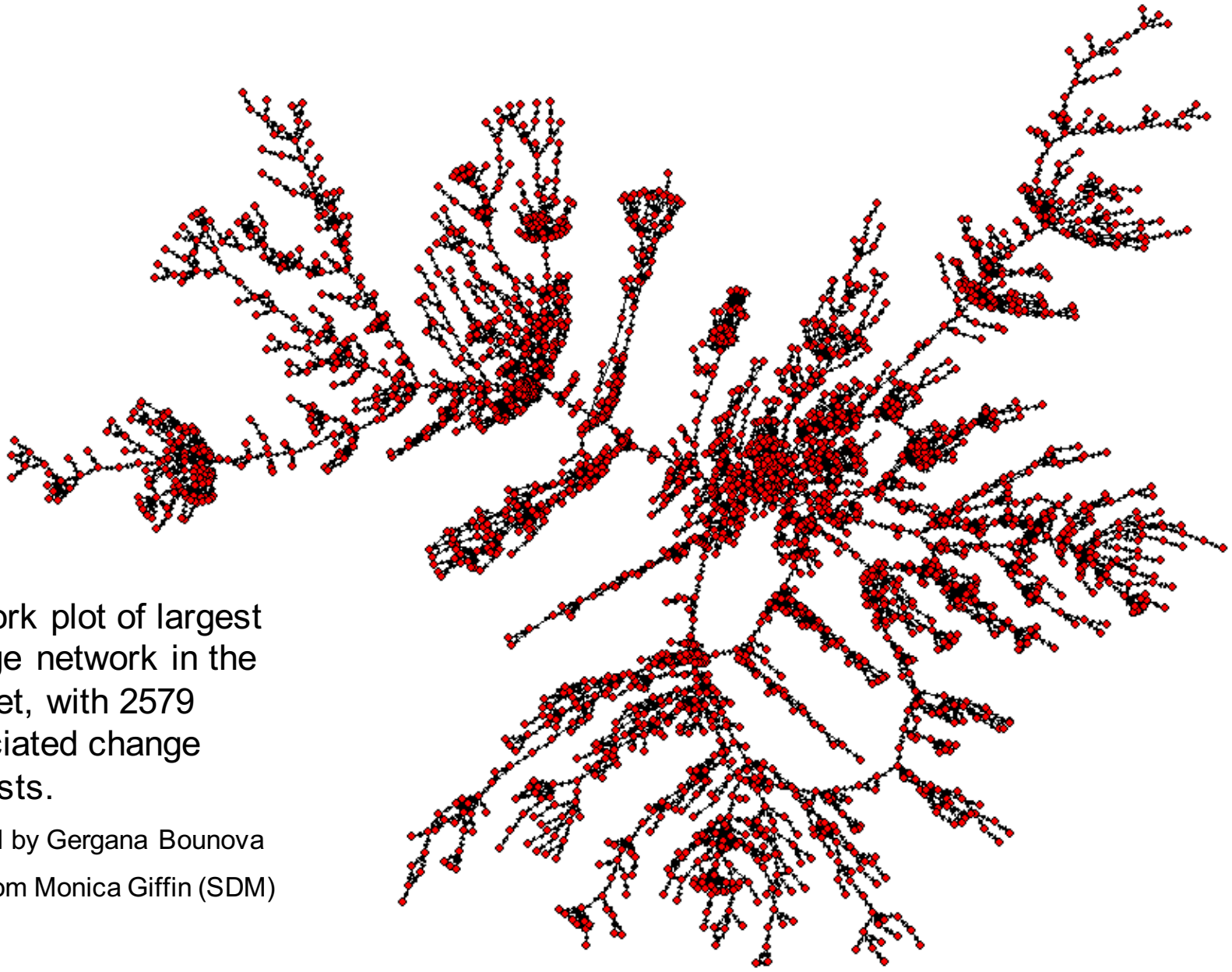
Change Networks

- Apply Graph Theory to extract networks of connected changes
  - parent-child changes
  - sibling changes
- Most changes are only loosely connected
  - 2-10 related changes
- Some large networks emerged
- Question: do these networks emerge from a single initial change?



No, Change Network Coalescence !

Change Propagation Network

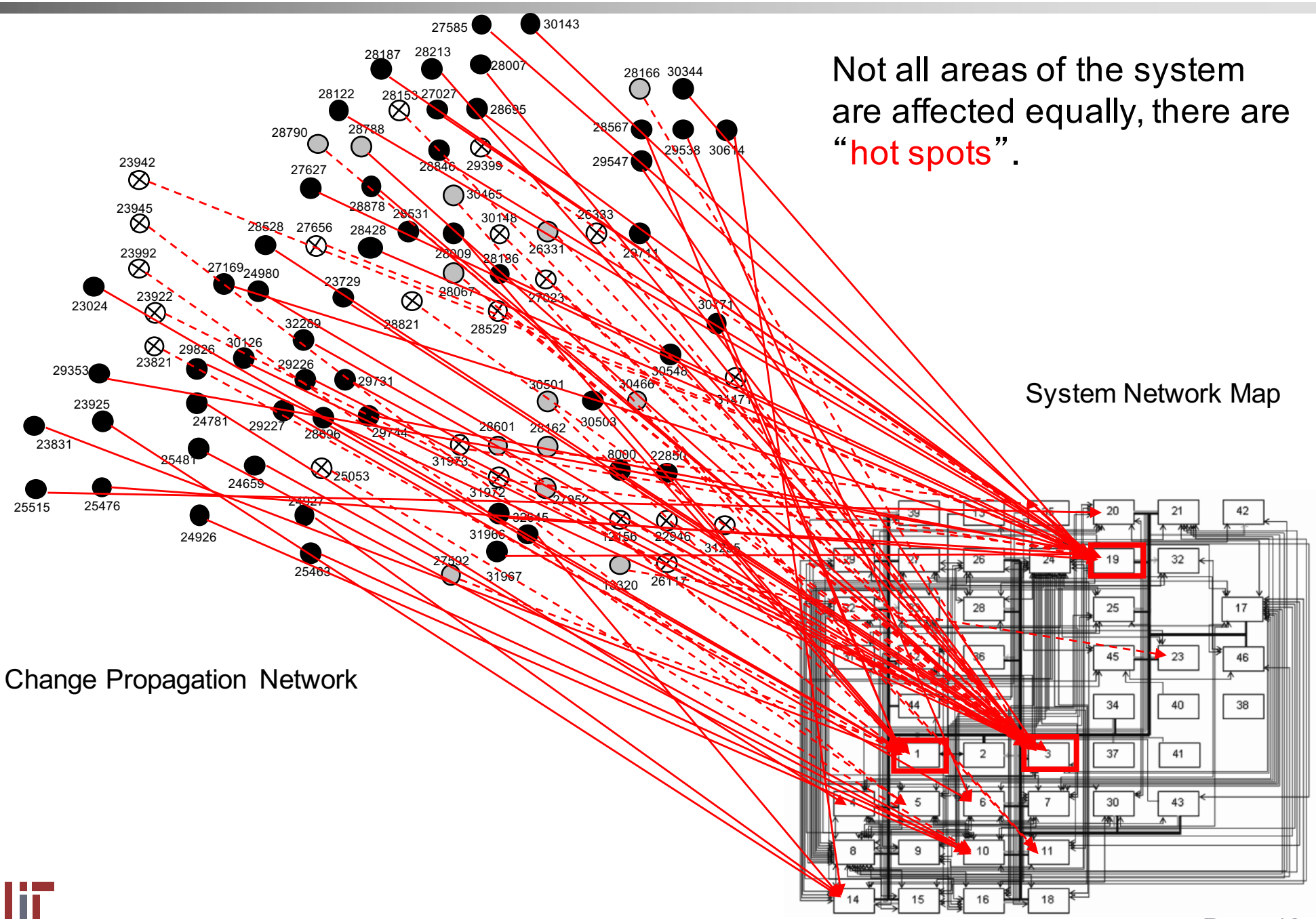


Network plot of largest change network in the dataset, with 2579 associated change requests.

Created by Gergana Bounova

Data from Monica Giffin (SDM)

Bi-Partite Graph Analysis (87-CR)



Change Propagation Index (CPI)

- Classify each area
  - Absorber, Carrier, Multiplier

change propagation probability

$$p_{ij} = \frac{\sum c_{ij}(parent) + \sum c_{ij}(sibling)}{C_{tot}(j)}$$

total completed changes in Area j

instigating area

ΔDSM Change Propagation Frequency

Area	1	2	3	4	5	6
1	0.4843	0.0011	0.0136	0.0057	0.0125	0.0023
2	0.0061	0.0000	0.0000	0.0030	0.0000	0.0000
3	0.0173	0.0000	0.1053	0.0050	0.0012	0.0000
4	0.0224	0.0000	0.0112	0.0449	0.0000	0.0000
5	0.0137	0.0000	0.0000	0.0000	0.1262	0.0000
6	0.0417	0.0000	0.0000	0.0000	0.0000	0.0833

receiving area

Also earlier work With Prof. Eun Suk Suh

$$C_{in}(i) = \sum_{j=1}^{N} \left(p_{ij} \times C_{tot}(j) \right)$$

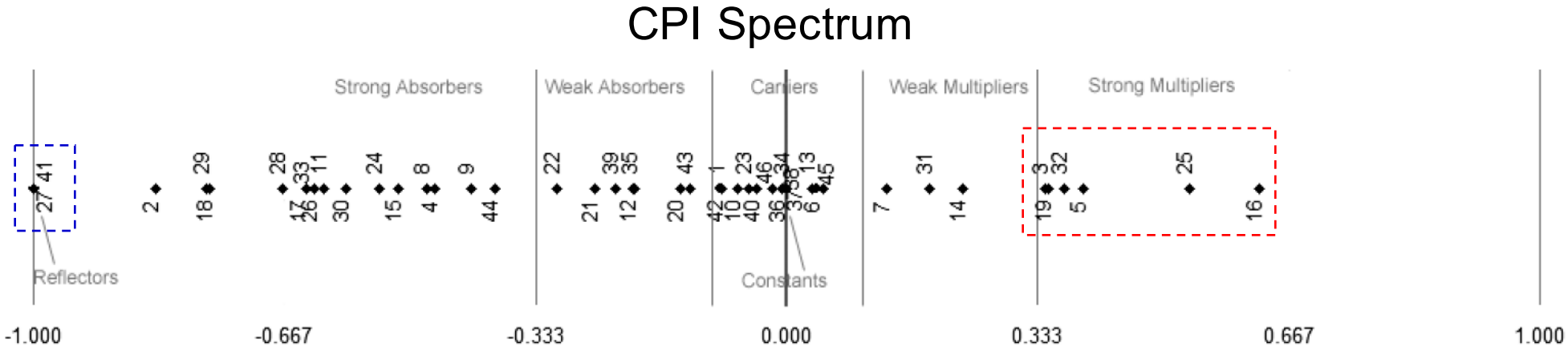
A change in Area 1 caused changes in Area 6 with a frequency of 4.17%.

$$C_{out}(i) = \sum_{j=1}^{N} \left(p_{ji} \times C_{tot}(i) \right)$$

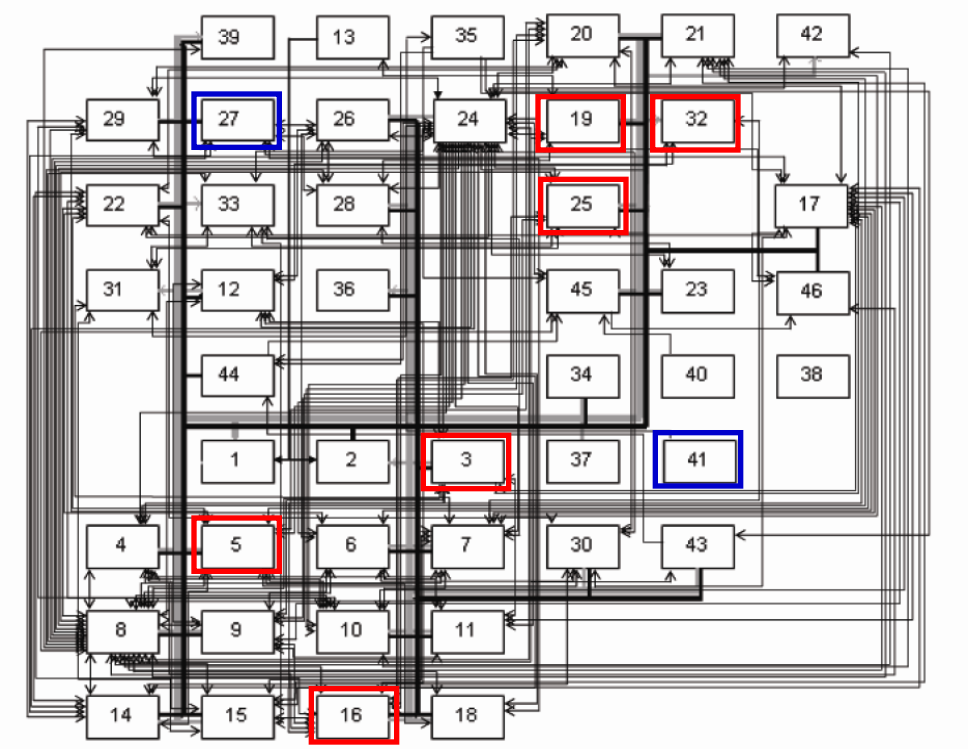
$$CPI(i) = \frac{C_{out}(i) - C_{in}(i)}{C_{out}(i) + C_{in}(i)}$$

-1 <= CPI <= +1

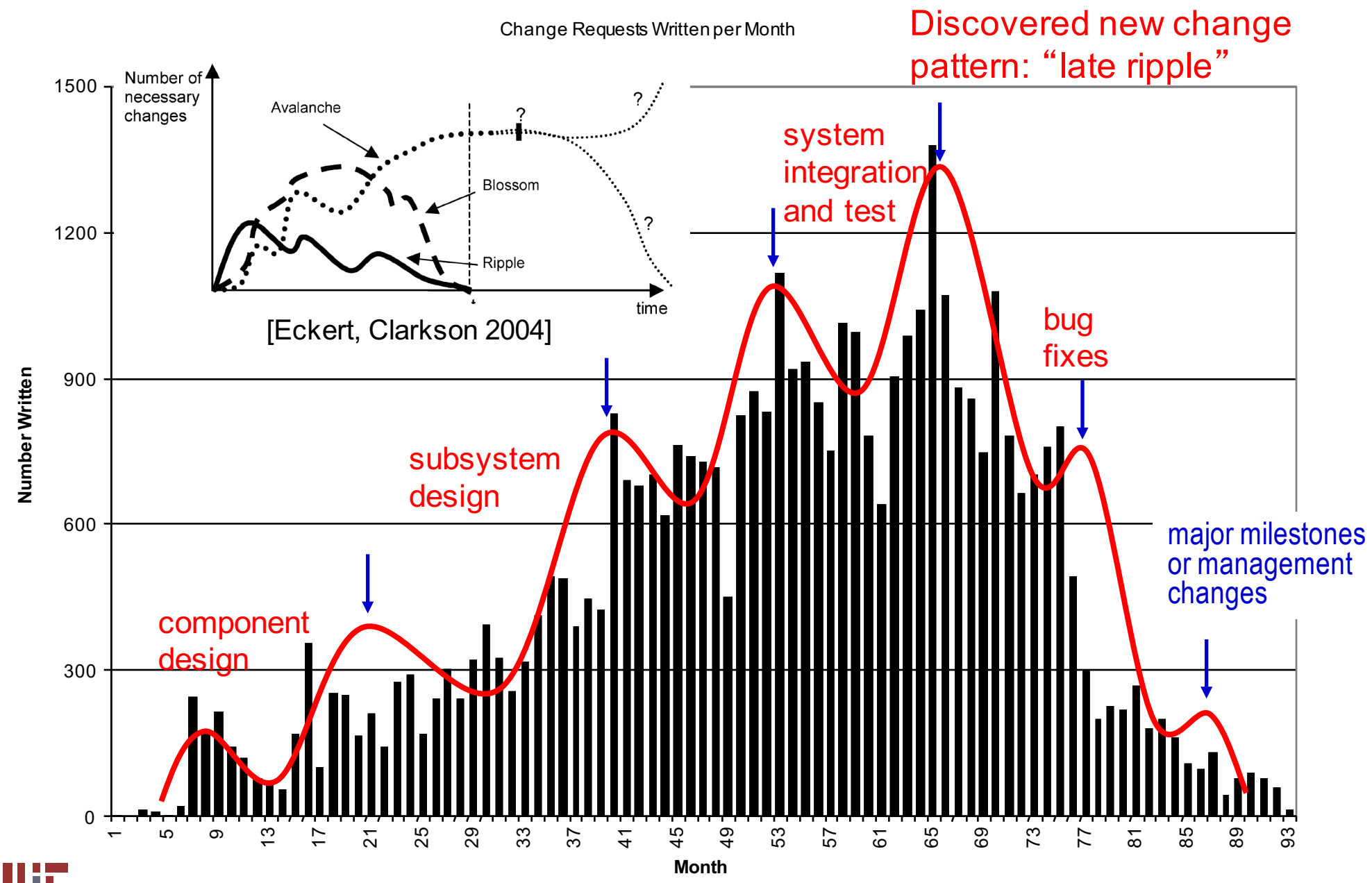
System Area Classification



- Areas found to be strong multipliers
  - 16: hardware performance evaluation
  - 25: hardware functional evaluation
  - 5: core data processing logic
  - 32: system evaluation tools
  - 19: common software services
  - 3: graphical user interface (GUI)
- Areas found to be perfect reflectors
  - 27, 41: look like perfect absorbers
  - but actually zero changes implemented
  - despite numerous changes proposed
  - = perfect reflectors



Change Request Generation Patterns



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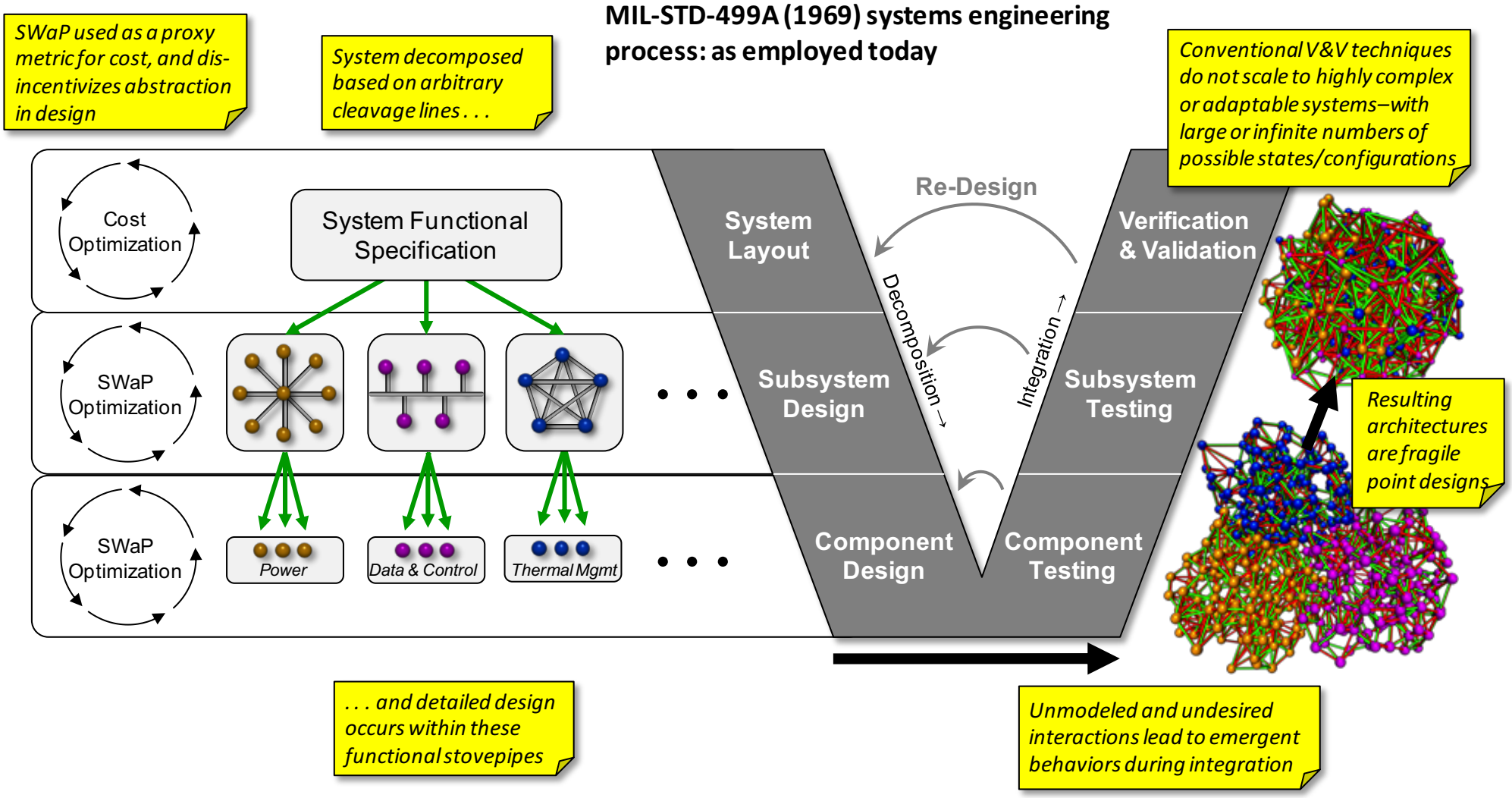
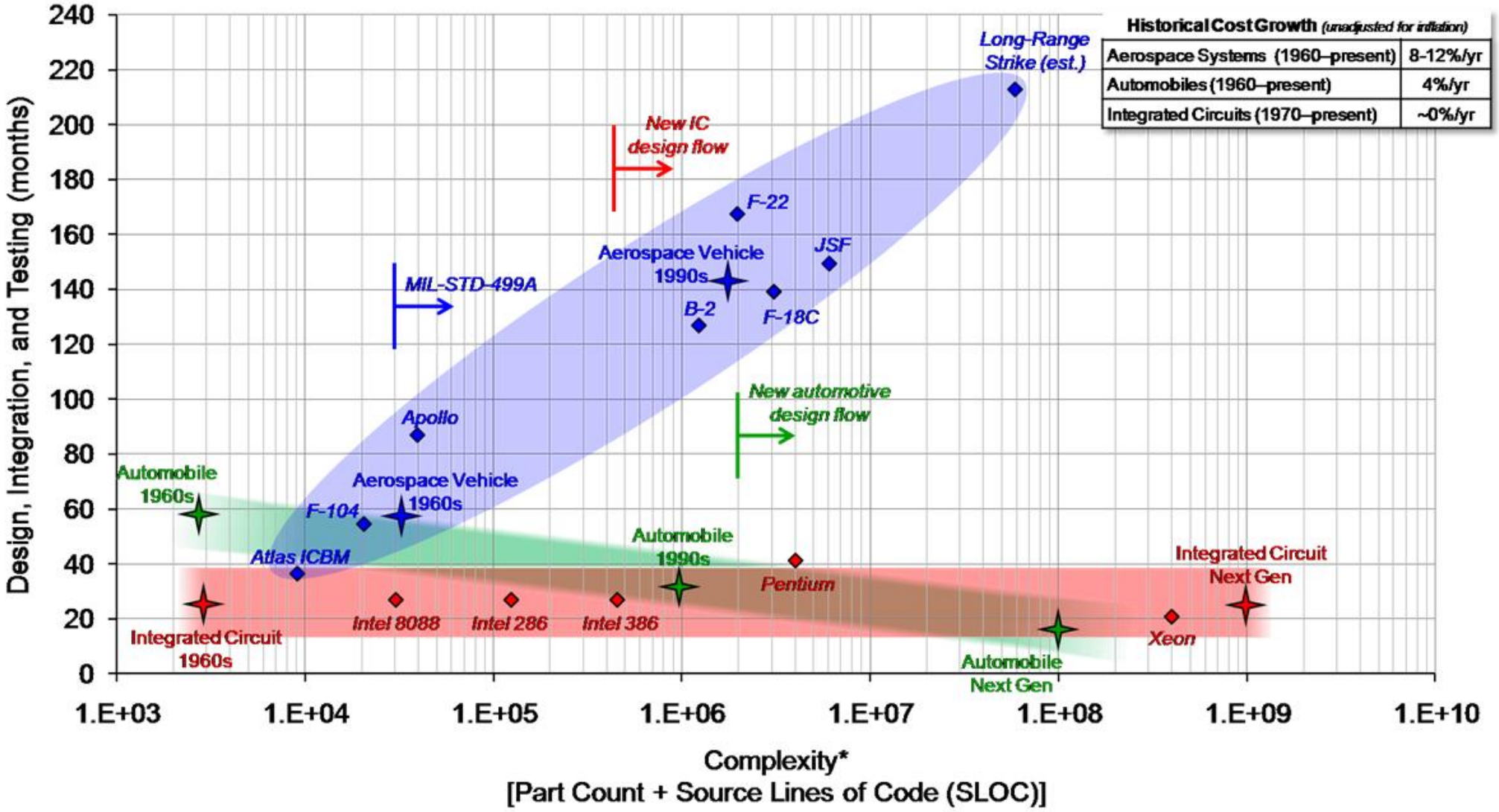
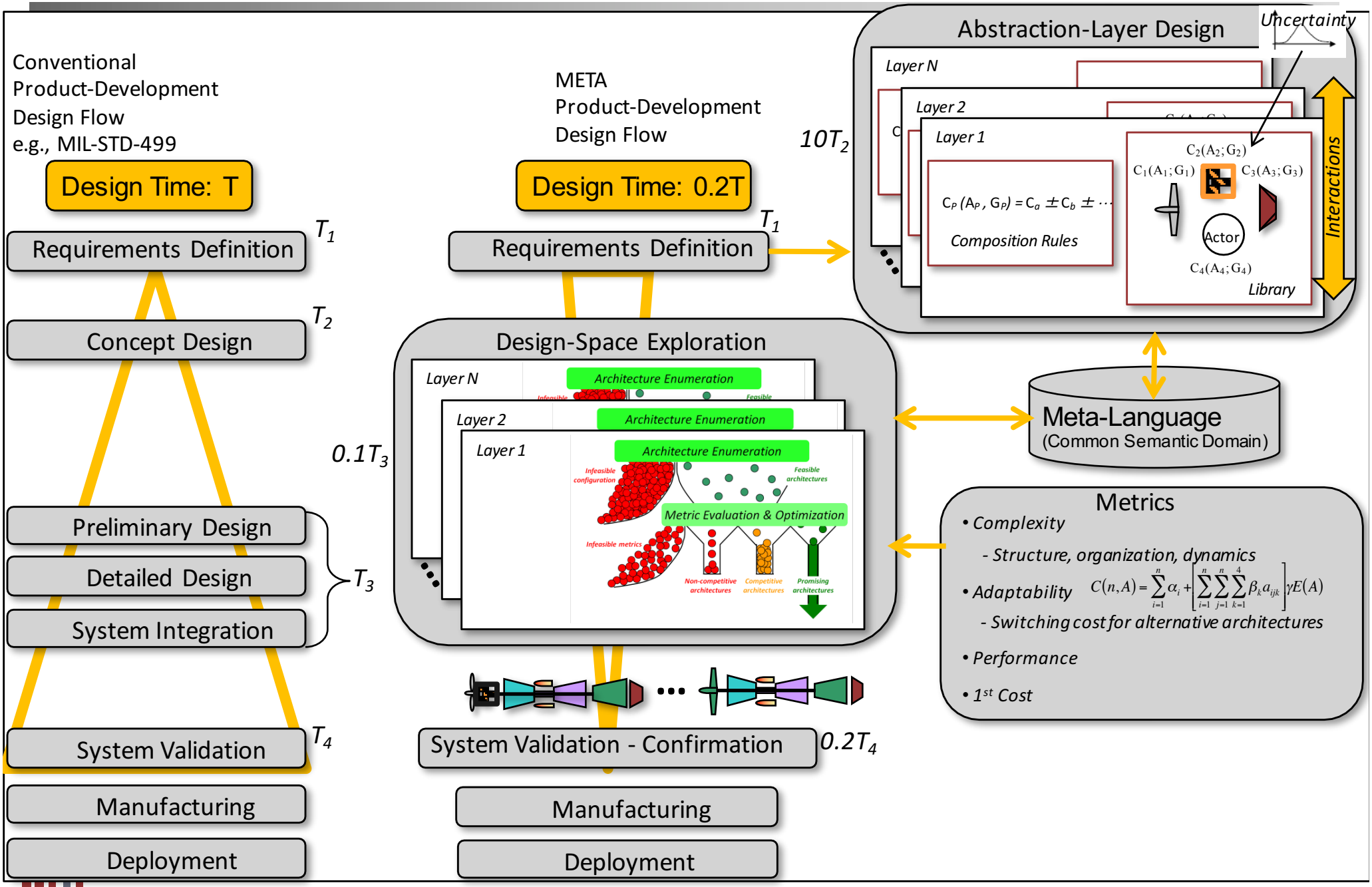
Status quo approach for managing complexity



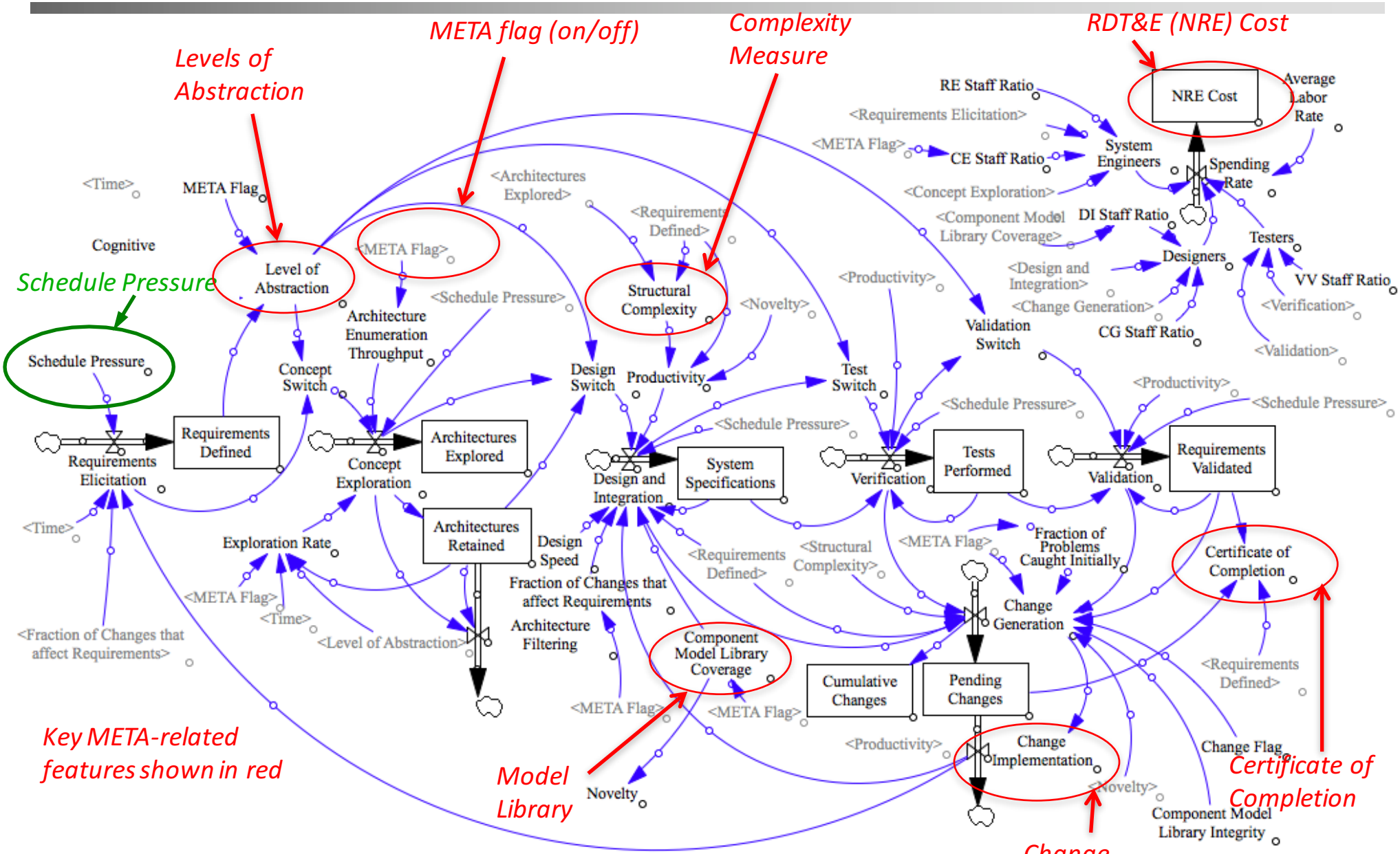
Historical schedule trends with complexity



META Approach to 5x acceleration of SE



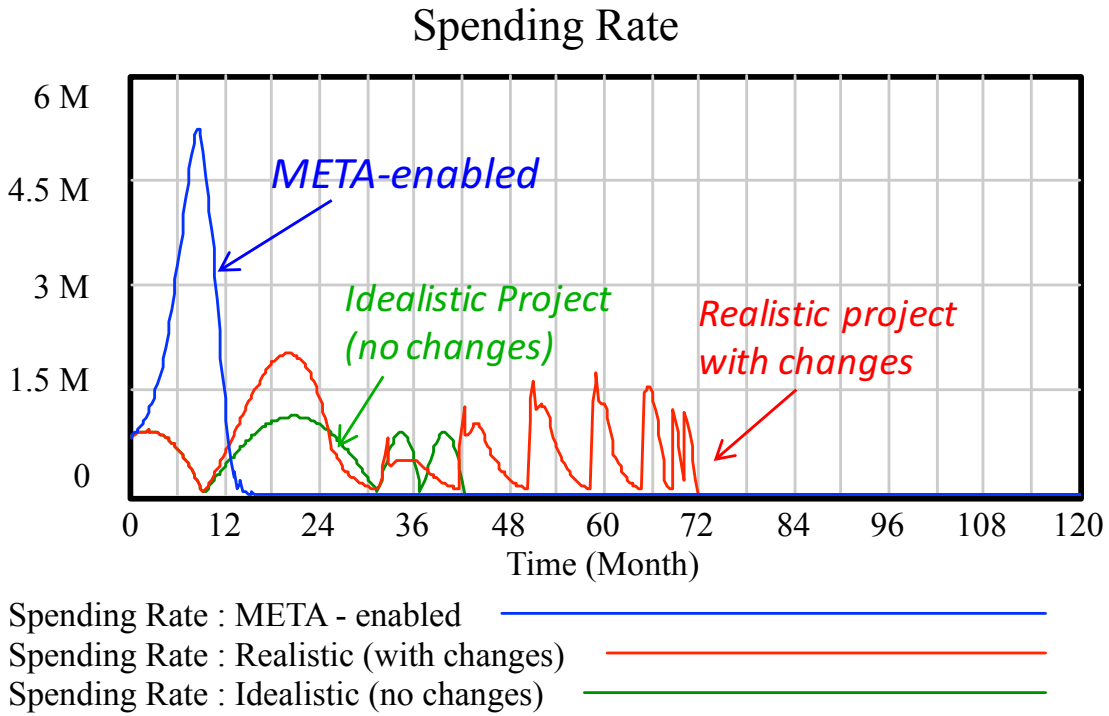
Vensim Model of META (5x) Process



de Weck O.L., "Feasibility of a 5x Speedup in System Development due to META Design", Paper DETC2012-70791, ASME 2012 International Design Engineering Technical Conferences (IDETC) and Computers and Information in Engineering Conference (CIE) Chicago, Illinois, August 12-15, 2012

Benchmark Case Results (3,000 requirements)

Simulation Case	Schedule to complete	NRE $ to complete
Idealistic Project	42.25 months	$27.9M
Realistic Project w/changes	70 months	$51.9M
META-enabled project	15.75 months	$31.5M



Simulation Assumptions:

All: Schedule Pressure = 1.5

META: 3-layers of abstraction (CB=9)

META: C2M2L library coverage: 50%

META: Novelty: 50%

META: C2M2L library integrity: 80%

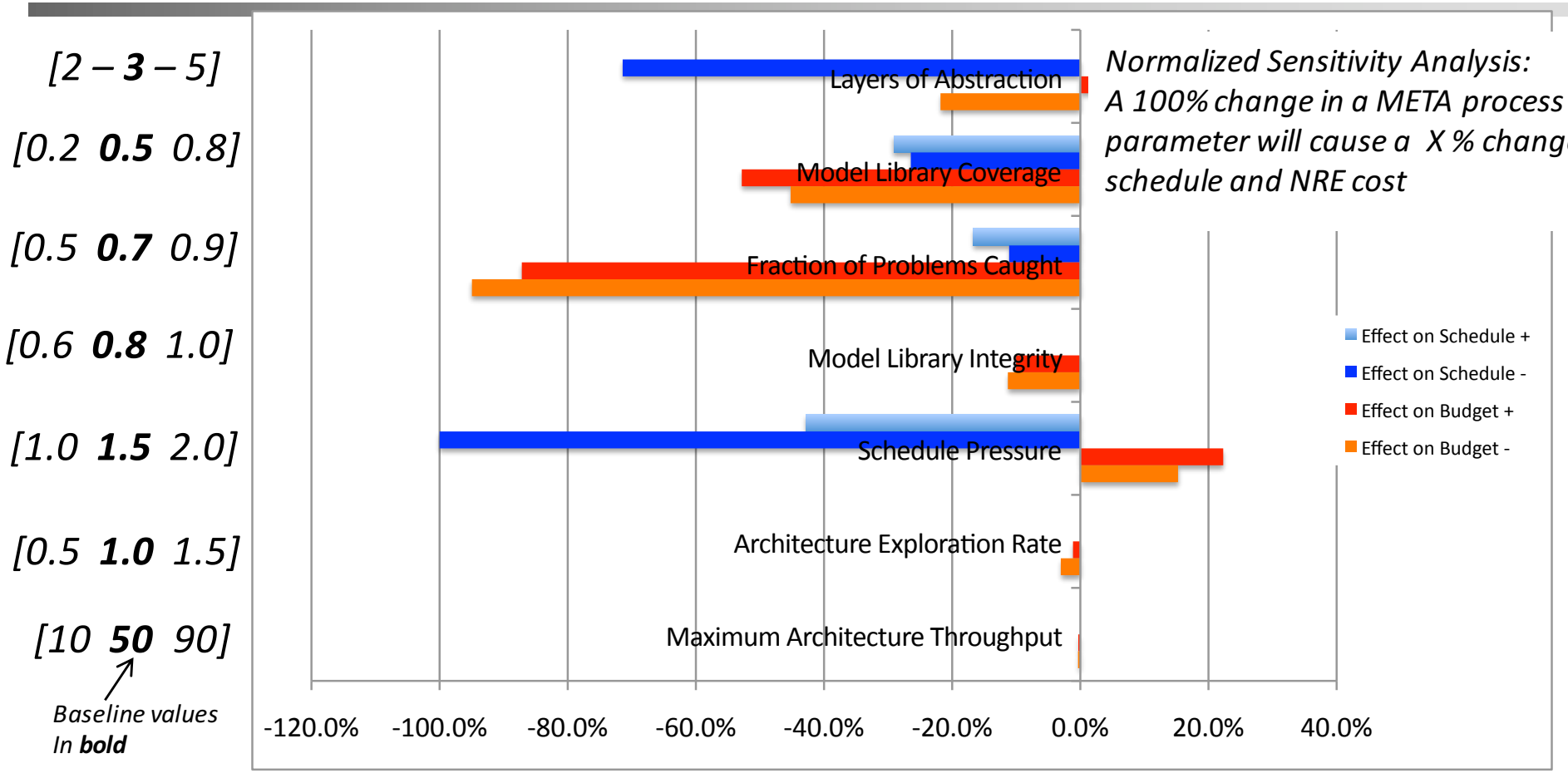
Problems caught early: 70%

Key Result:

META speedup factor = 70/16=4.4

Confirmed that META speedup of 5x is possible but cost reduction is only 1.5 x !

META-Enablers Sensitivity Analysis is very revealing !

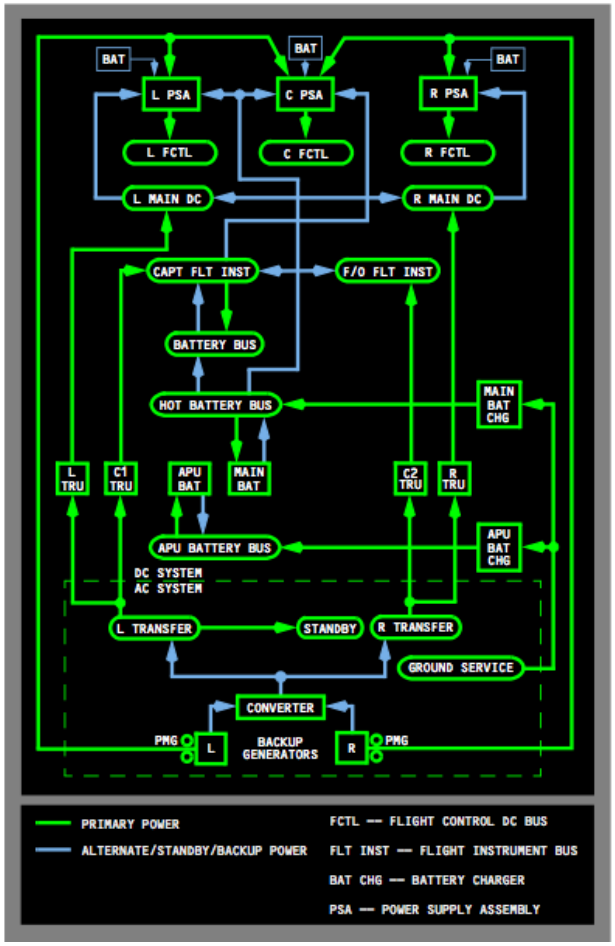


- Increasing **Layers of Abstraction** from 2 → 3 significantly improves schedule, there is much less benefit in going from 3 → 4 or from 3 → 5
- C2M2L **Model Library Coverage** (completeness) is key for both schedule and NRE
- META **ability to catch problems early has big budget impact**
- **Schedule Pressure** speeds up schedule – also in META - but costs more

Validation: 777 Electric Power System (EPS)

- Project Parameters from Hamilton Sundstrand:
  - 5 Years– Feb 1990 (project work authorized) – Jan 1995 (final qualification test complete)
  - Source control drawing was completed in 1993 This is the complete equipment spec.
  - Number of customer requirements: ~1,500
  - Number of Change Request: ~300
  - Total number of major components: 33
    - 2 Integrated Drive Generators (IDG); 1 auxiliary generator (APU driven); 3 Generator Control Units; 1 Bus Power Control Unit; 24 Current Transformers; 2 Quick attach/detach Units
  - Ratio of systems people working CDR to people working Qualification test was 1:1.5

DC and Flight Control Electrical Systems Schematic

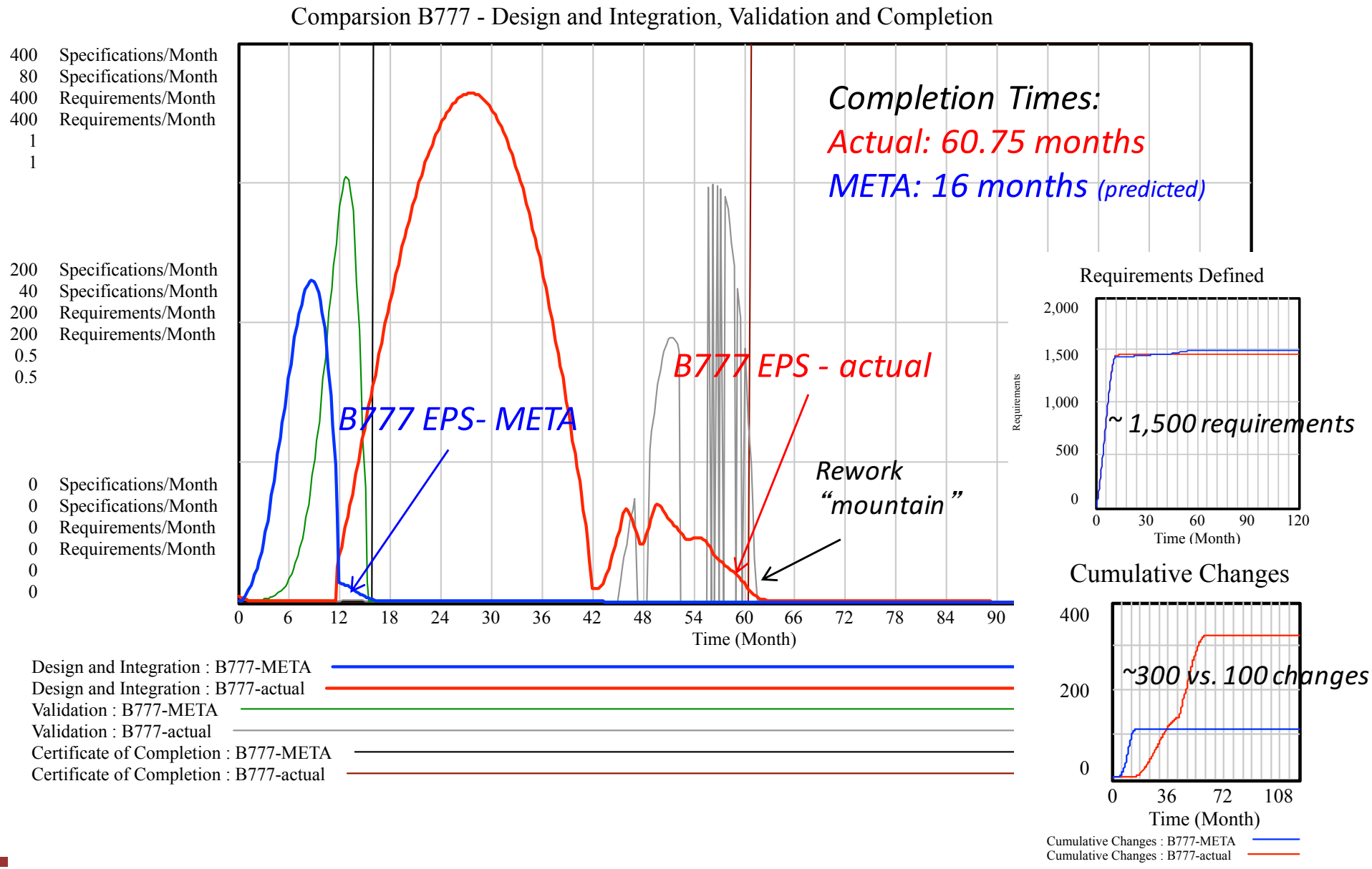


Approach:

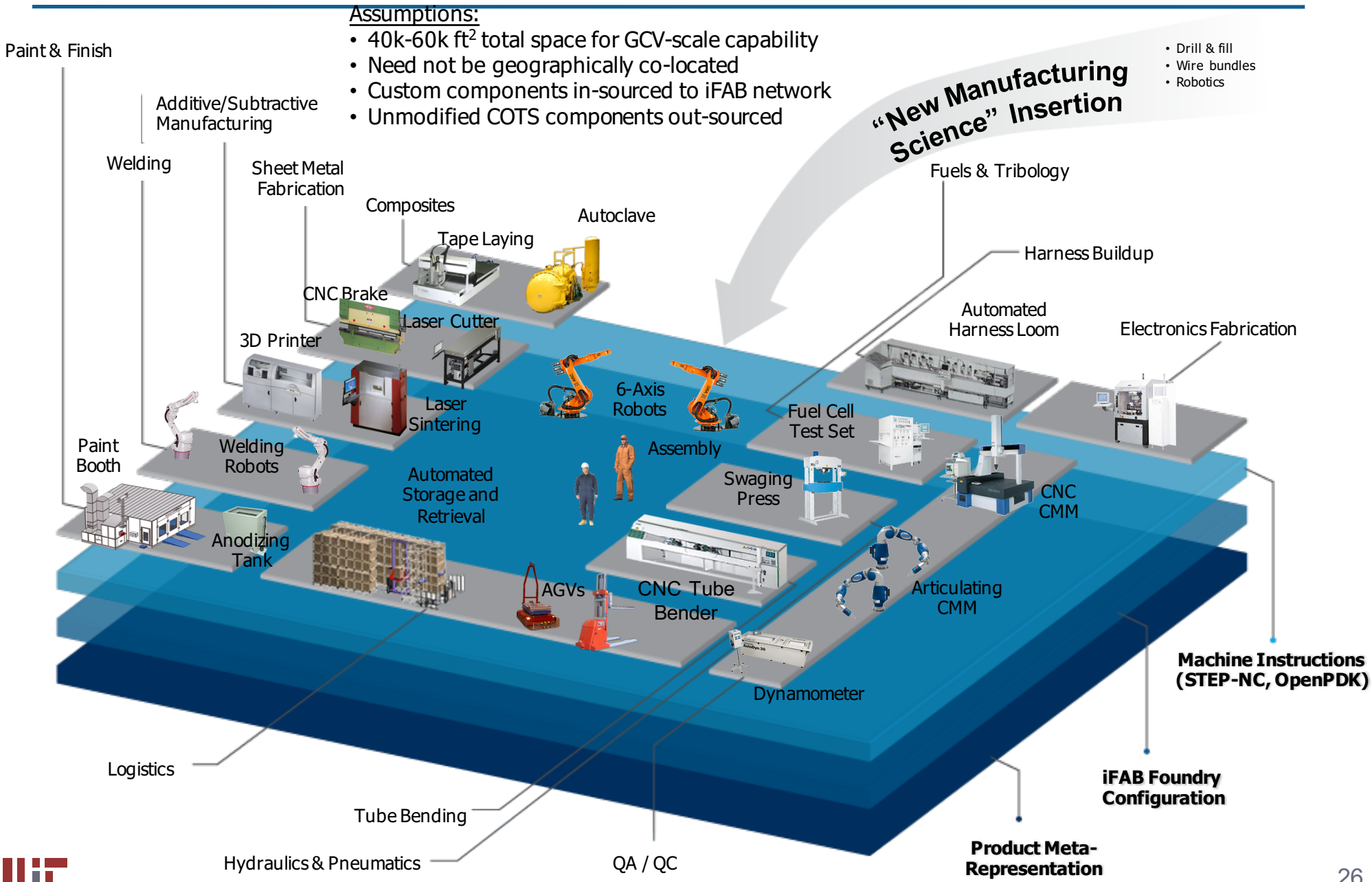
1. Approximately simulate B777 EPS Program execution

2. Simulate META version of B777 EPS and see impact

Comparison of B777 EPS Program (actual vs. META)

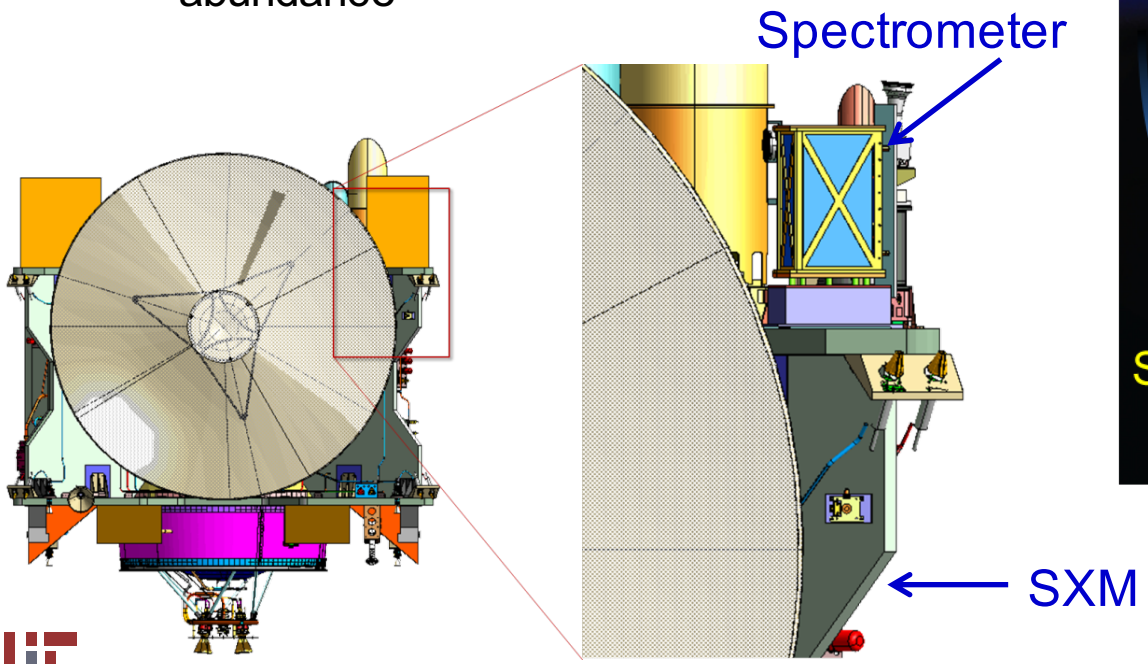


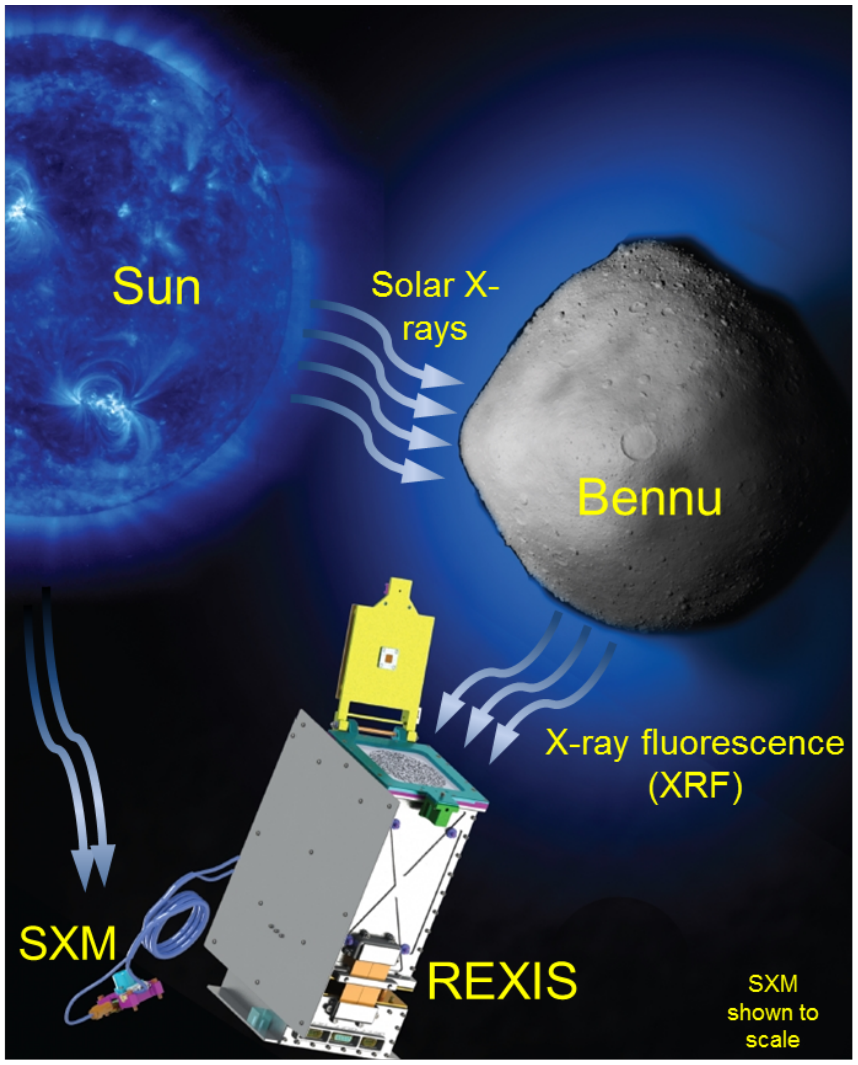
A bitstream-programmable, "foundry-style" factory



MBSE Case Study: REXIS

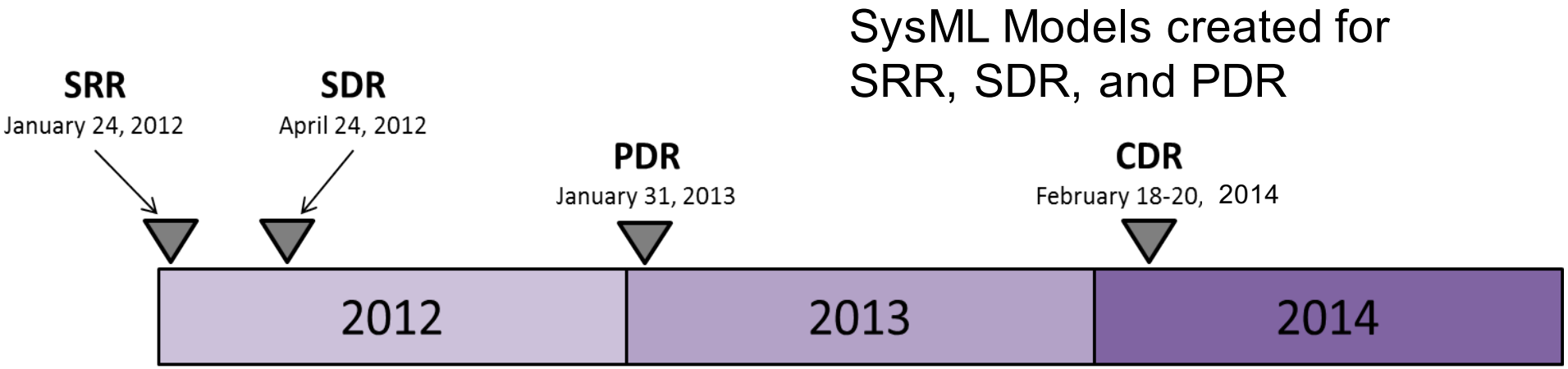
- One of six instruments on the OSIRIS-REX asteroid sample return
- Launch happened on Sept 8, 2016
- Measures X-rays that are fluoresced from 101955 Bennu
- Fluorescent line energies depend on the atomic structure of the matter
  - Provides a unique elemental signature
  - Line strengths reflect element abundance





Credit: Mark Chodas

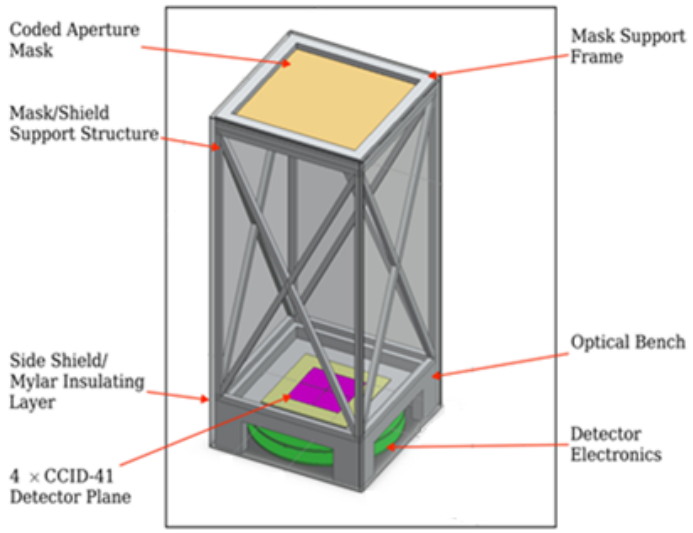
REXIS Design History Overview



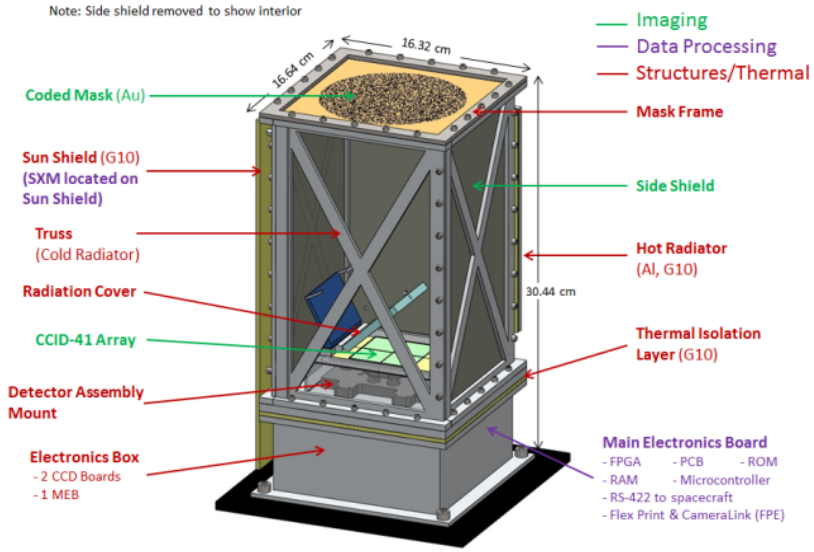
- SysML models created at SRR, SDR, and PDR

- From Fall 2011 through Spring 2012, REXIS team composed primarily of undergraduates
  - With grad students and faculty mentors
- From Summer 2012 to present, REXIS team composed primarily of grad students
  - With faculty mentors and undergraduate volunteers

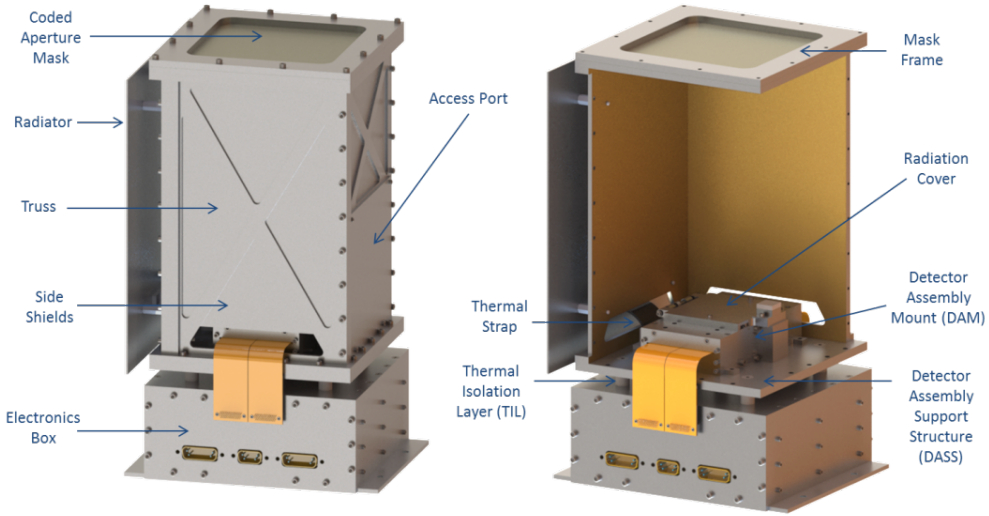
REXIS Design History



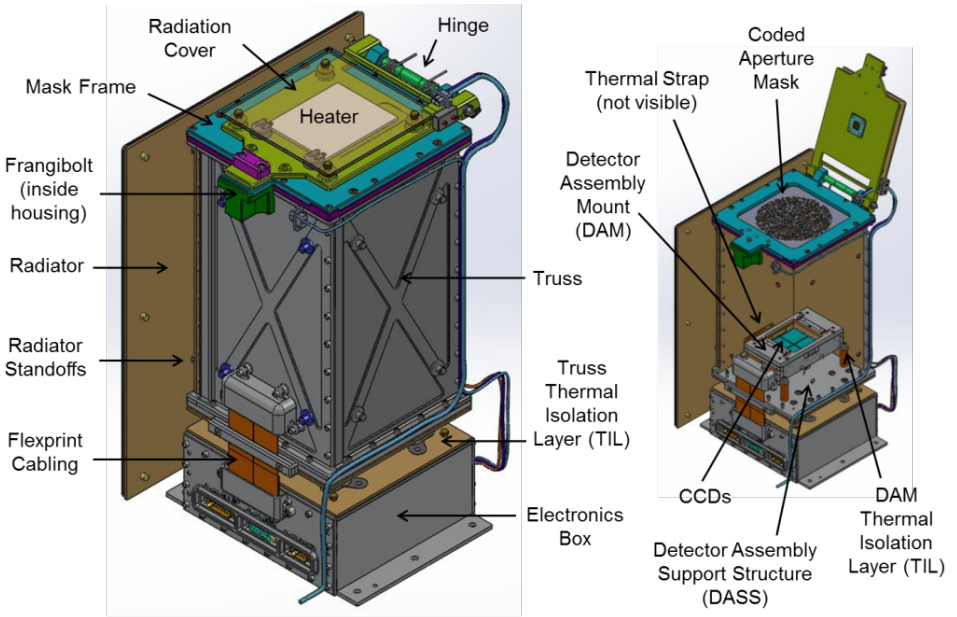
SRR - January 2012



SDR - April 2012



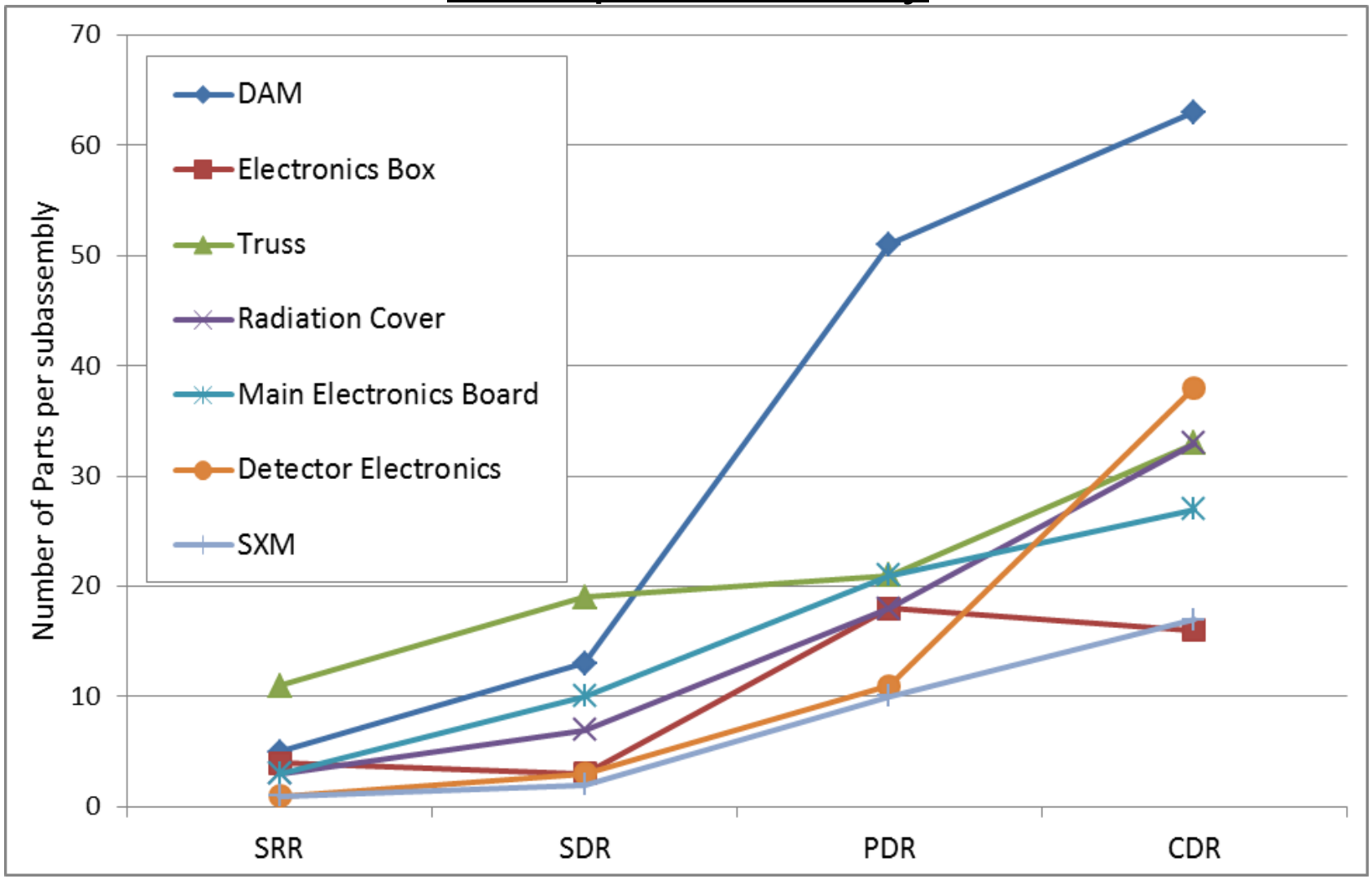
PDR - January 2013



CDR - February 2014

REXIS Design History Statistics

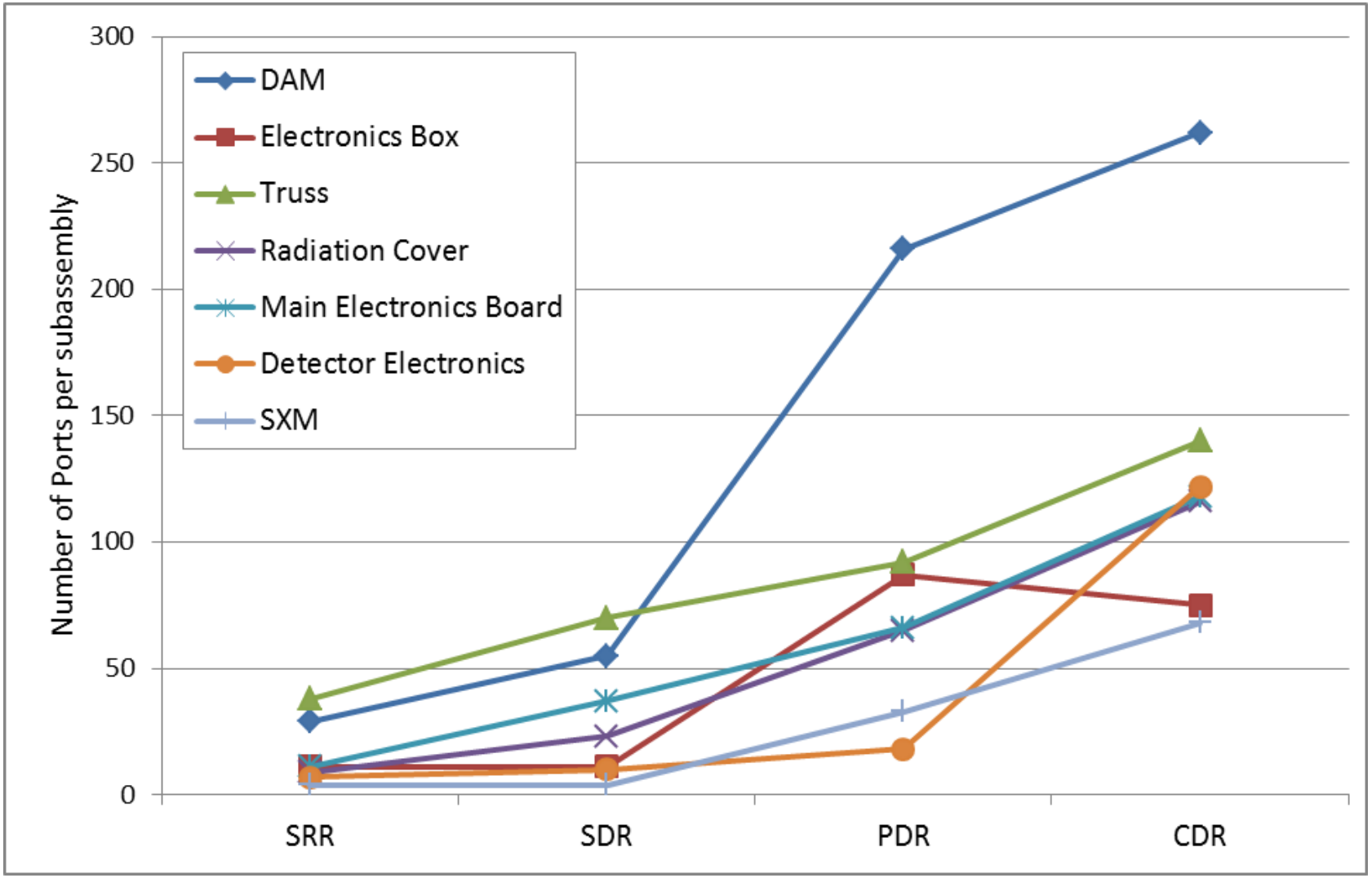
Parts per Assembly



All assemblies experienced parts growth

REXIS Design History Statistics (cont.)

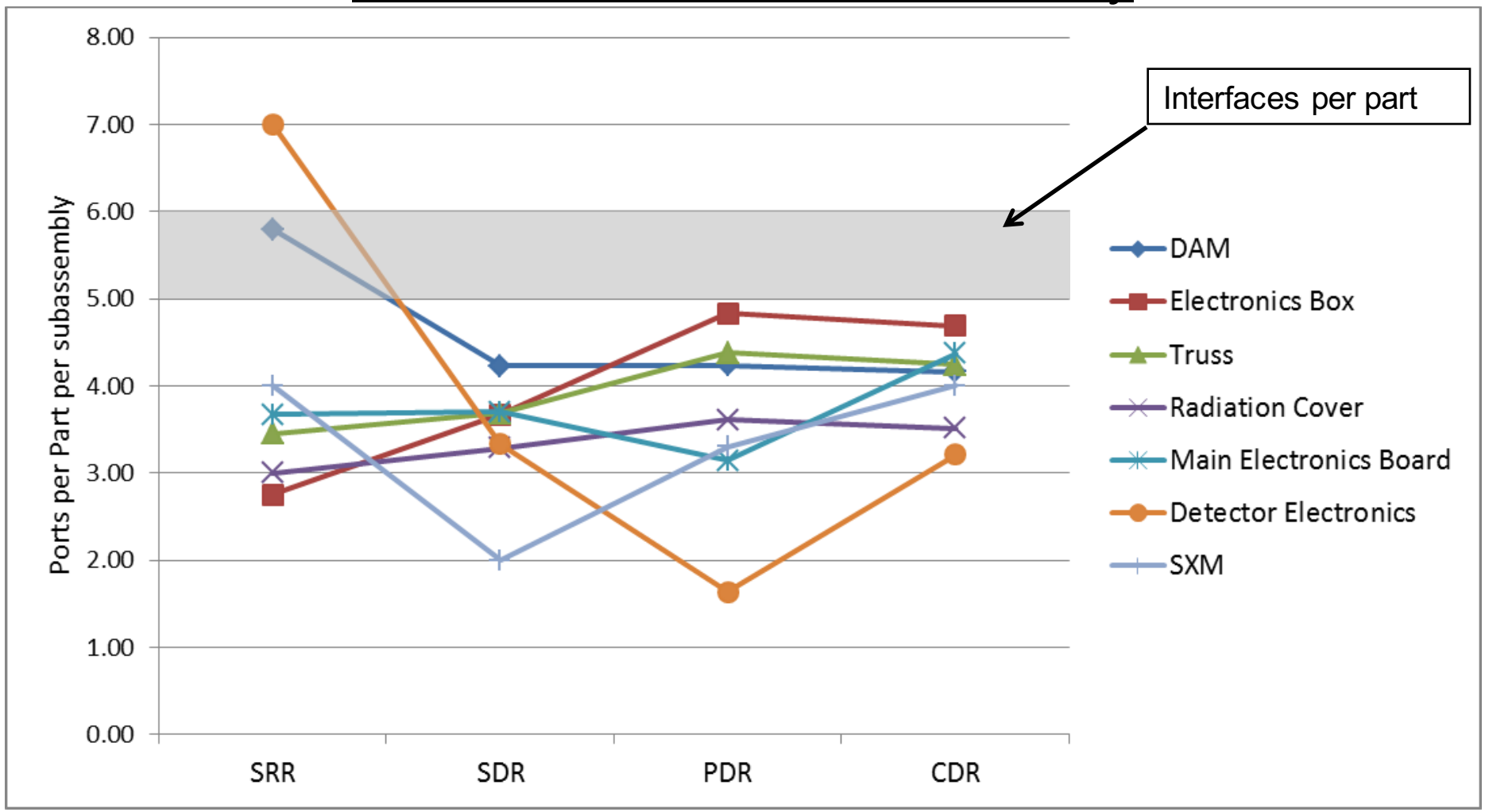
Ports per Assembly



All assemblies experienced interface growth

REXIS Design History Statistics (cont.)

Ports Per Part in each Assembly



Average number of interfaces per part is invariant as design matures from SRR to CDR

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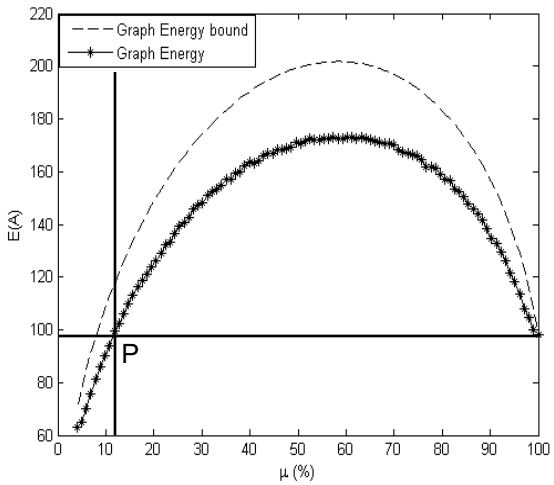
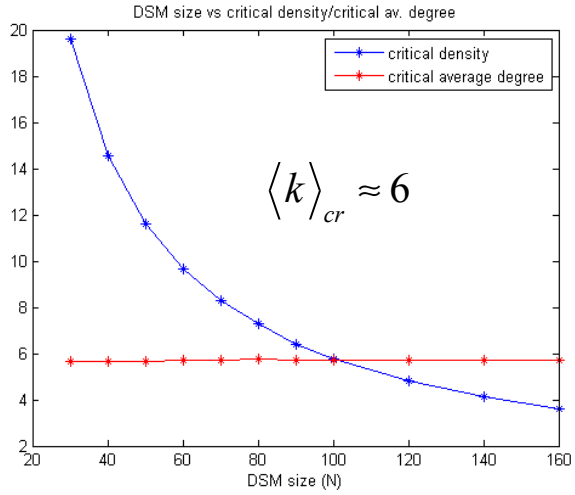
SE today and "Utopia" in 2041

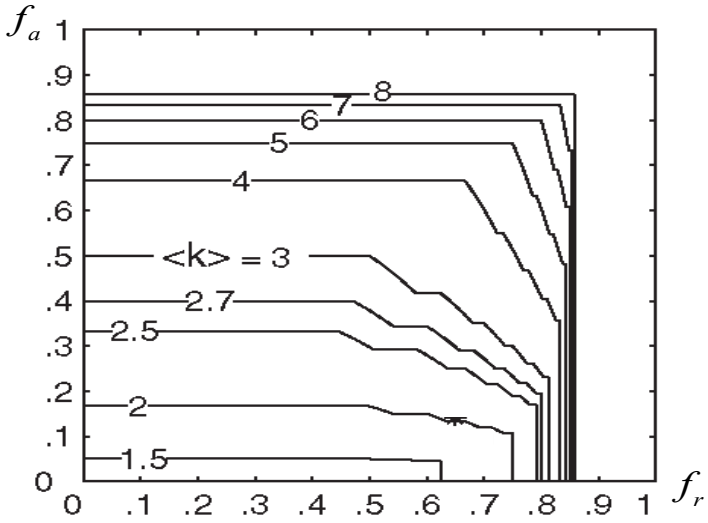
- **SE today**
  - Systems Engineering has transitioned to adulthood in 25 years
  - SE has spread to many industries incl. medical devices etc.
  - MBSE: Moving from documents to interactive models
  - META: Design systems from libraries of components using compositional rules and guarantees of correctness . Speedup 4-5x.
  - **YES, we are much further along.**

- **SE "Utopia" in 25 years**
  - We design "elegant" systems with only essential complexity
  - Every physical system has a model-based "digital twin"
  - There is a "Nobel Prize" awarded for Systems Engineering
  - **The 1st, 2nd, ... law of systems science and engineering** is well established and widely accepted (similar to thermodynamics)

1st Law of SE: *Conservation of Complexity*

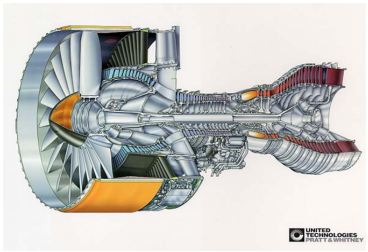


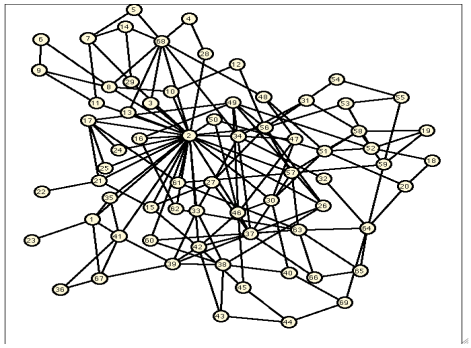


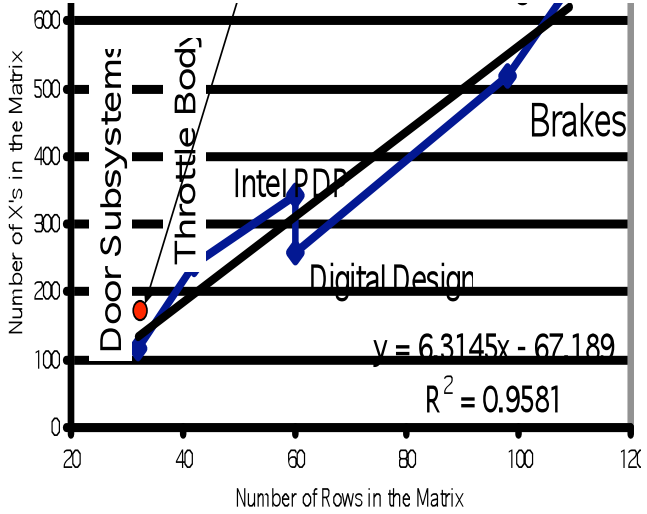


Network resilience contour (f_r vs. f_a) [Valente et al., 2004]

At a critical nodal degree $\langle k \rangle_{cr} = 6$ systems transition from a lower-complexity hierarchical to a higher-complexity distributed architecture. Essential complexity is conserved.







[Whitney et al., 1999]

Systems Engineering:

From Adolescence to Adulthood (1991-2016)

- **Many thanks for your attention**
- **Consider submitting a manuscript to the INCOSE Wiley Journal *Systems Engineering***

  http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1520-6858