



Massachusetts  
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ÉCOLE POLYTECHNIQUE  
FÉDÉRALE DE LAUSANNE

# Fundamentals of Systems Engineering

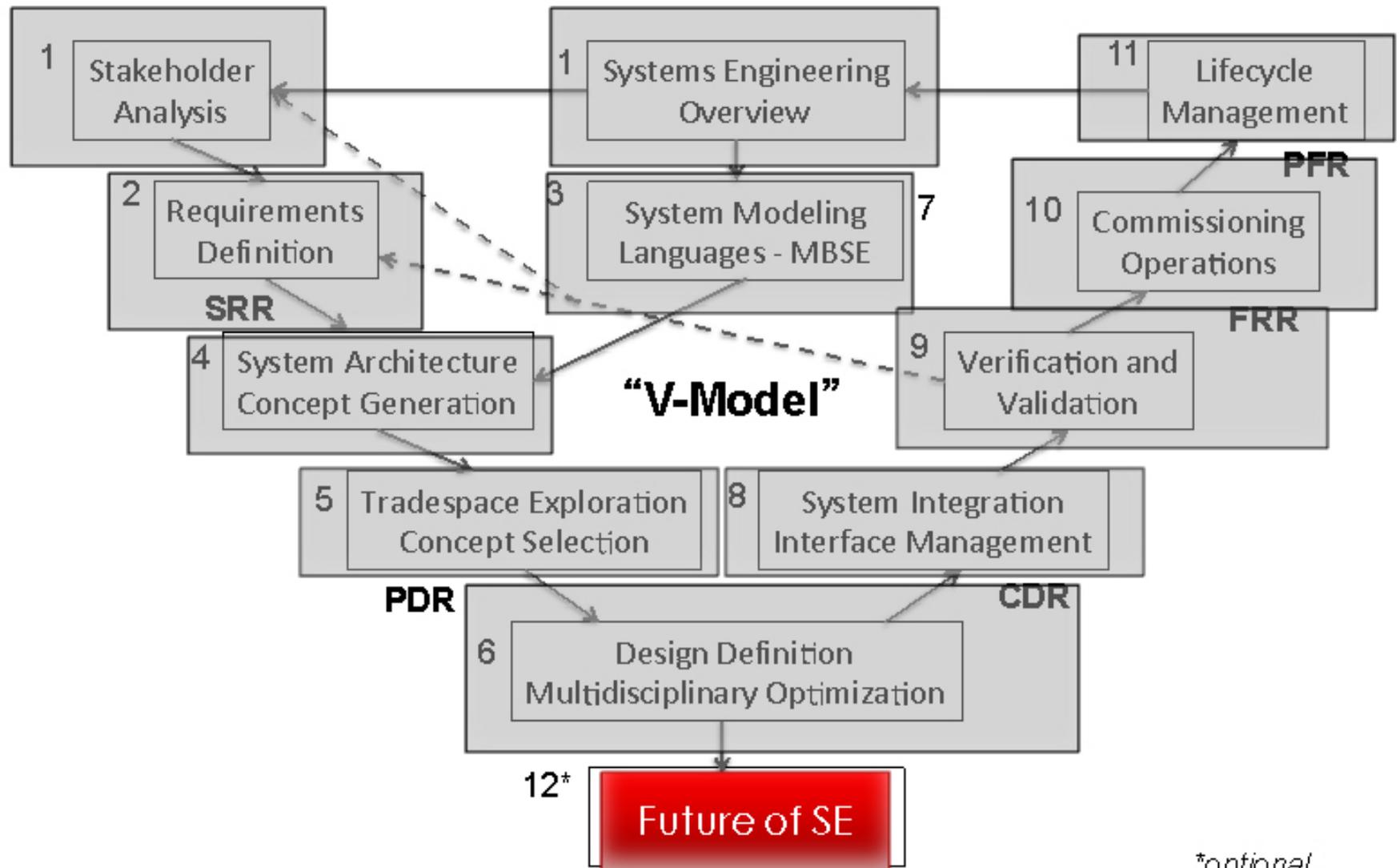
Prof. Olivier L. de Weck

## **Session 12**

Future of Systems Engineering

# The “V-Model” of Systems Engineering

16.842/ENG-421 Fundamentals of Systems Engineering



*\*optional*

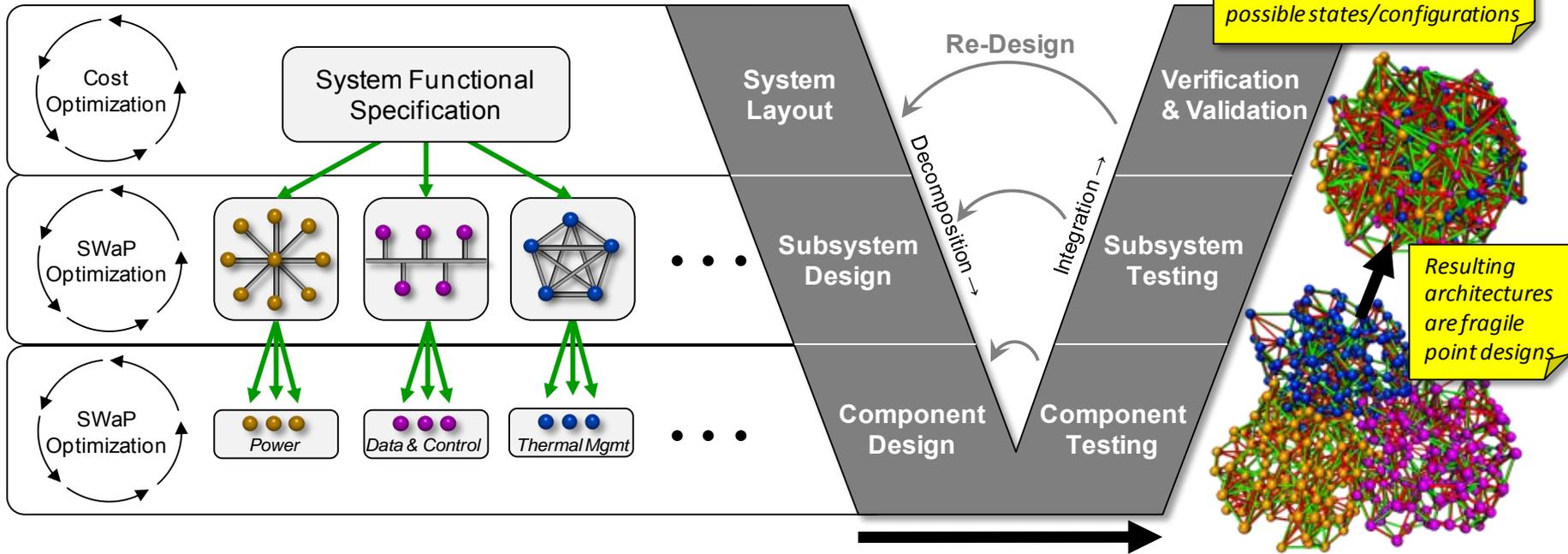
# Status quo approach for managing complexity in SE

SWaP used as a proxy metric for cost, and disincentivizes abstraction in design

System decomposed based on arbitrary cleavage lines . . .

MIL-STD-499A (1969) systems engineering process: as employed today

Conventional V&V techniques do not scale to highly complex or adaptable systems—with large or infinite numbers of possible states/configurations



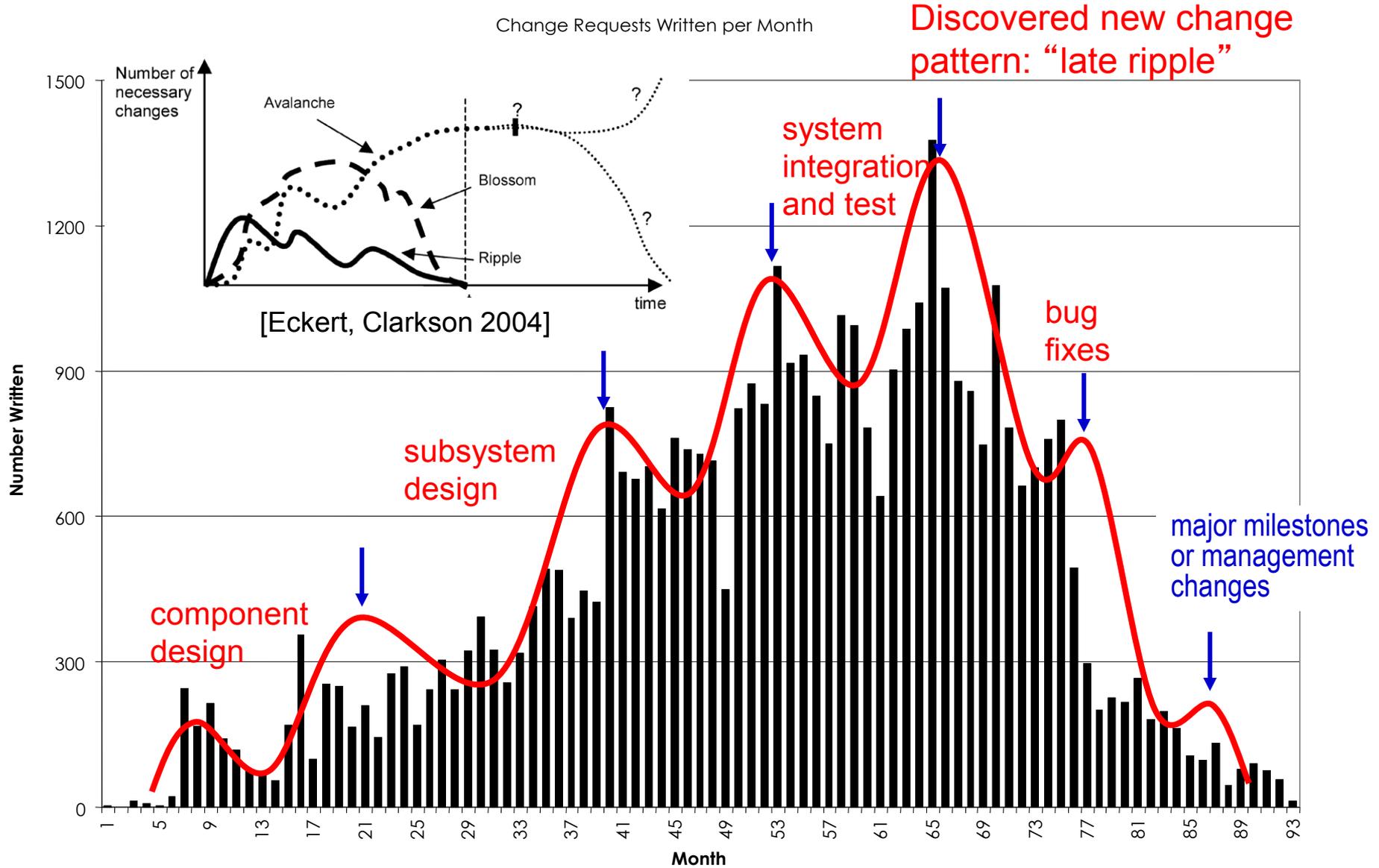
. . . and detailed design occurs within these functional stovepipes

Unmodeled and undesired interactions lead to emergent behaviors during integration

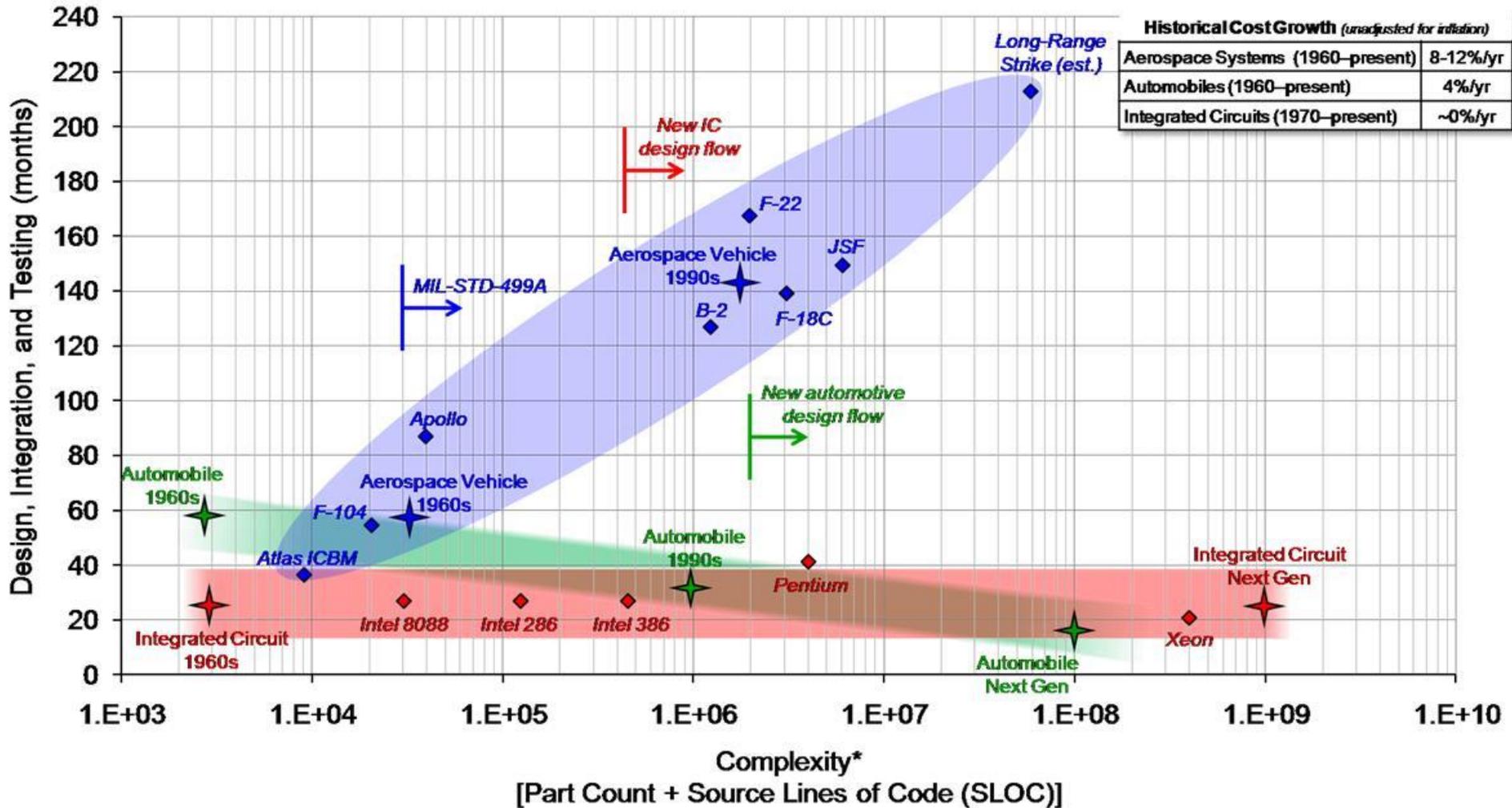
SWaP= Size, Weight, and Power  
V&V= Verification & Validation

Green = Desirable interactions (data, power, forces & torques)  
Red = Undesirable interactions (thermal, vibrations, EMI)

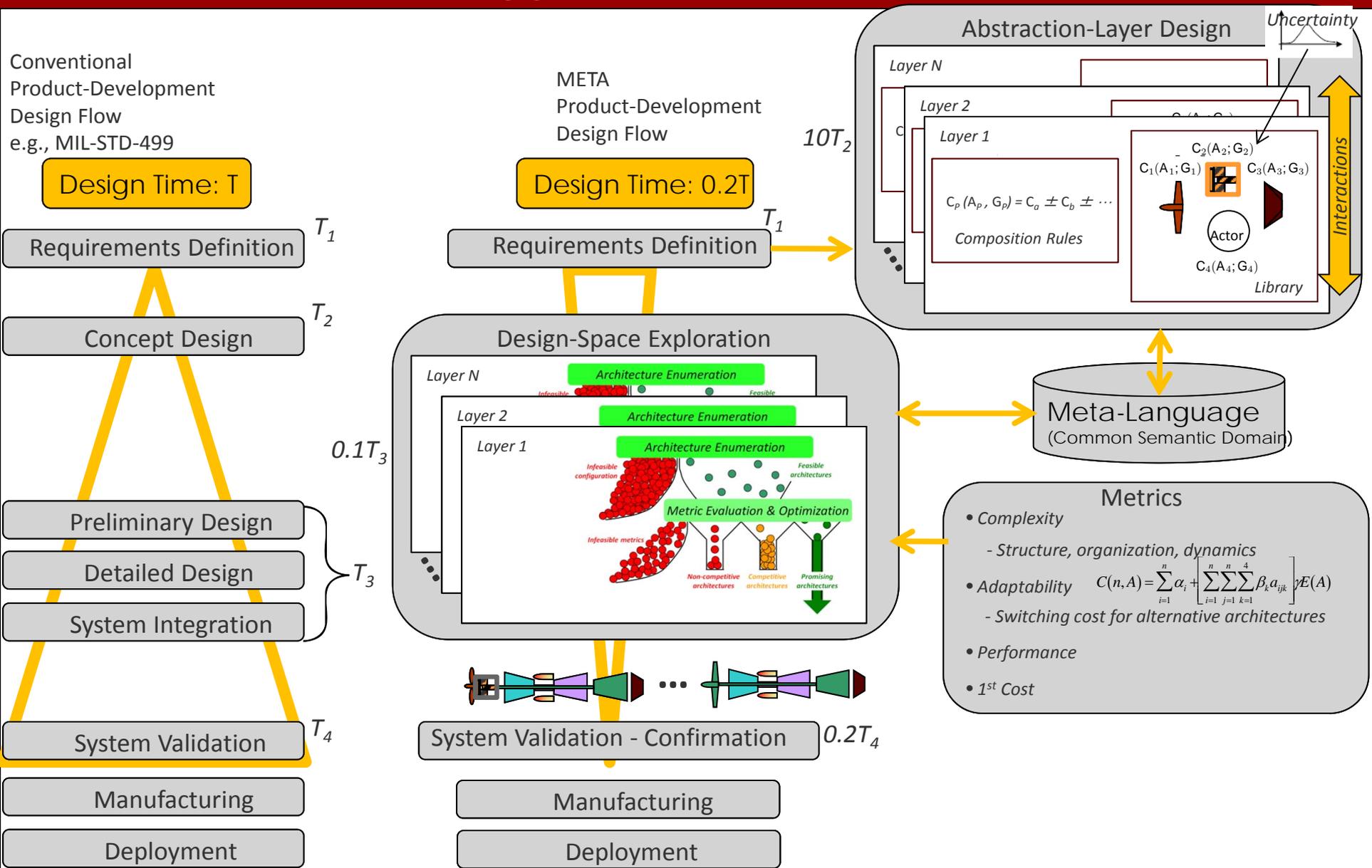
# Change Request Generation Patterns



# Historical schedule trends with complexity



# DARPA META Approach to 5x acceleration of SE





# A bitstream-programmable, "foundry-style" factory

## Assumptions:

- 40k-60k ft<sup>2</sup> total space for GCV-scale capability
- Need not be geographically co-located
- Custom components in-sourced to iFAB network
- Unmodified COTS components out-sourced

Paint & Finish

Additive/Subtractive Manufacturing

Welding

Sheet Metal Fabrication

Composites

Autoclave

Tape Laying

CNC Brake

Laser Cutter

3D Printer

Laser Sintering

6-Axis Robots

Assembly

Fuel Cell Test Set

Fuels & Tribology

Harness Buildup

Automated Harness Loom

Electronics Fabrication

Paint Booth

Welding Robots

Automated Storage and Retrieval

Swaging Press

CNC CMM

Anodizing Tank

CNC Tube Bender

Articulating CMM

AGVs

Dynamometer

Machine Instructions (STEP-NC, OpenPDK)

Logistics

Tube Bending

Hydraulics & Pneumatics

QA / QC

Product Meta-Representation

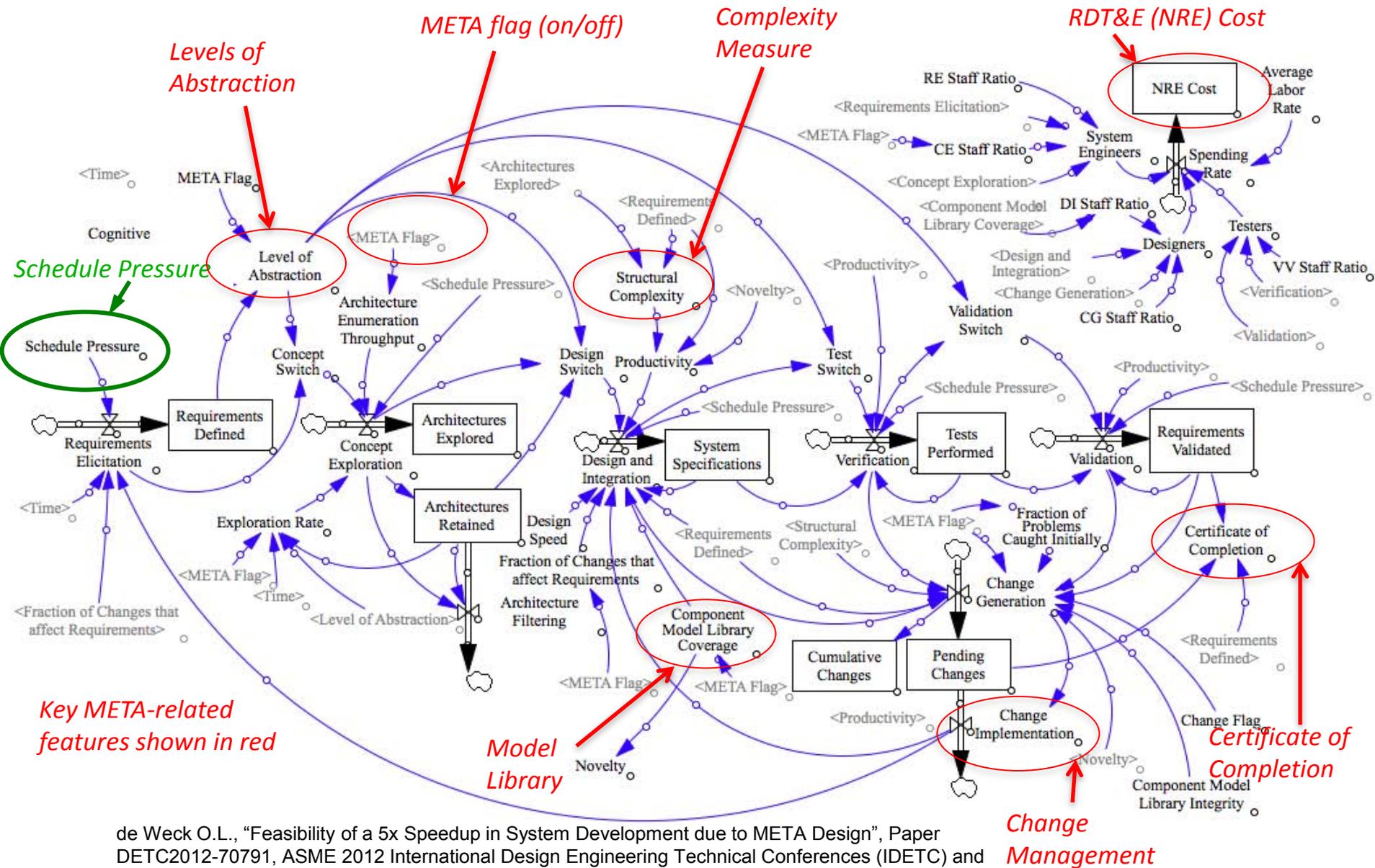
iFAB Foundry Configuration

**"New Manufacturing Science" Insertion**

- Drill & fill
- Wire bundles
- Robotics

This image is in the public domain.

# Vensim Model of META (5x) Process

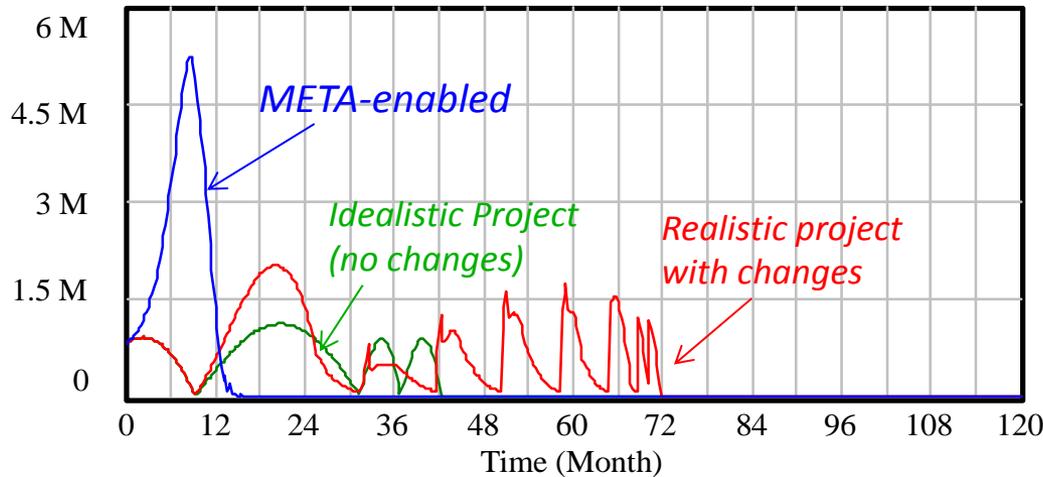


de Weck O.L., "Feasibility of a 5x Speedup in System Development due to META Design", Paper DETC2012-70791, ASME 2012 International Design Engineering Technical Conferences (IDETC) and Computers and Information in Engineering Conference (CIE) Chicago, Illinois, August 12-15, 2012

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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

Spending Rate



Spending Rate : META - enabled —————  
 Spending Rate : Realistic (with changes) —————  
 Spending Rate : Idealistic (no changes) —————

Simulation Assumptions:

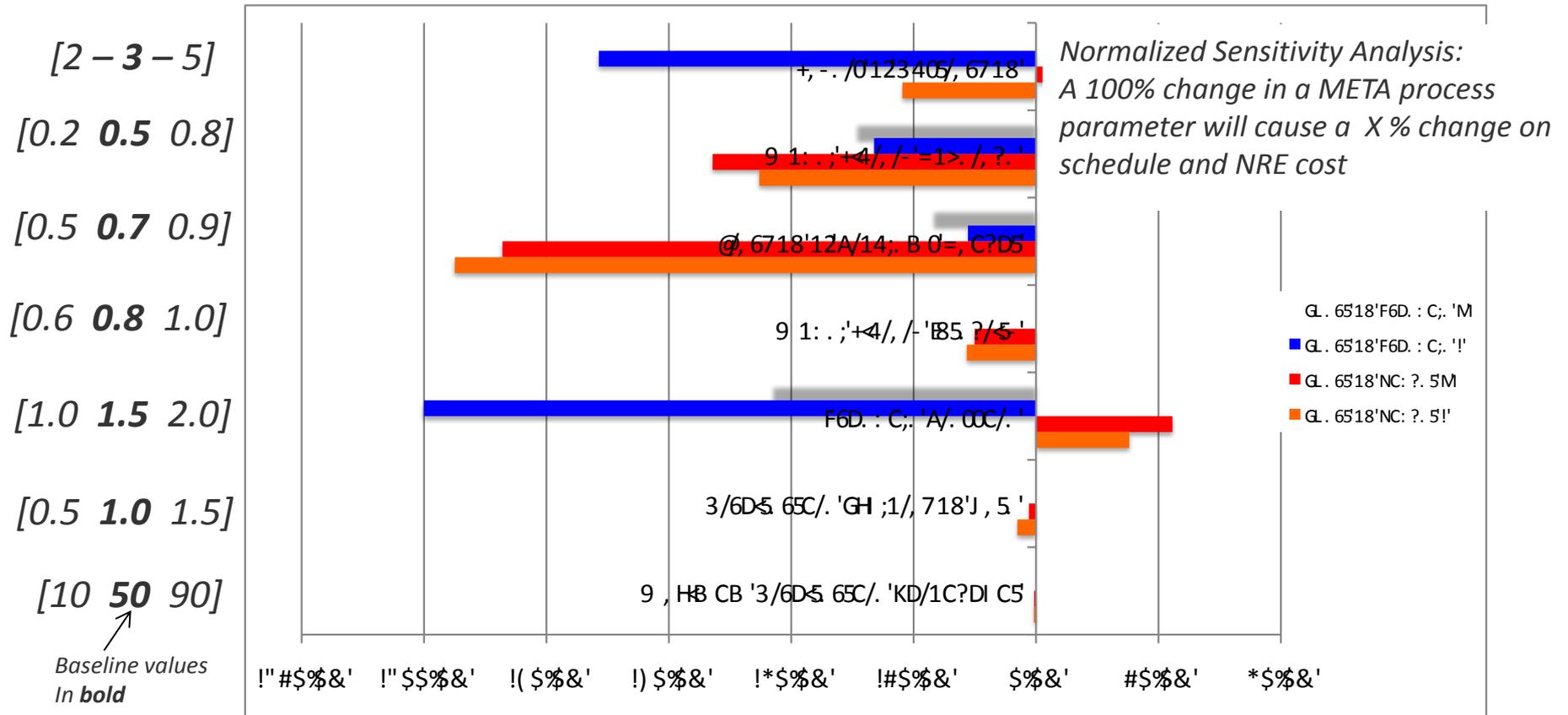
- All: Schedule Pressure = 1.5
- META: 3-layers of abstraction (CB=9)
- META: C2M2L library coverage: 50%
- META: Novelty: 50%
- META: C2M2L library integrity: 80%
- Problems caught early: 70%

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)

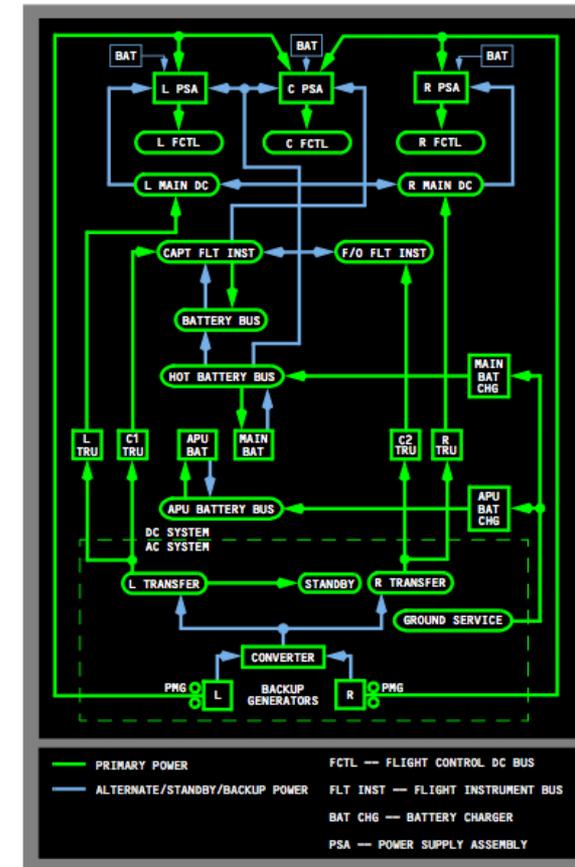
- Project Parameters from Hamilton Sundstrand:
  - **5 Years**– Feb 1990 (project work authorized) – Jan 1995 (final qualification test complete)
  - **Source control drawing** was completed in **1993**  
This is the complete equipment spec.
  - Number of customer requirements: **~1,500**
  - Number 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**

## Approach:

1. Approximately simulate B777 EPS Program execution
2. Simulate META version of B777 EPS and see impact

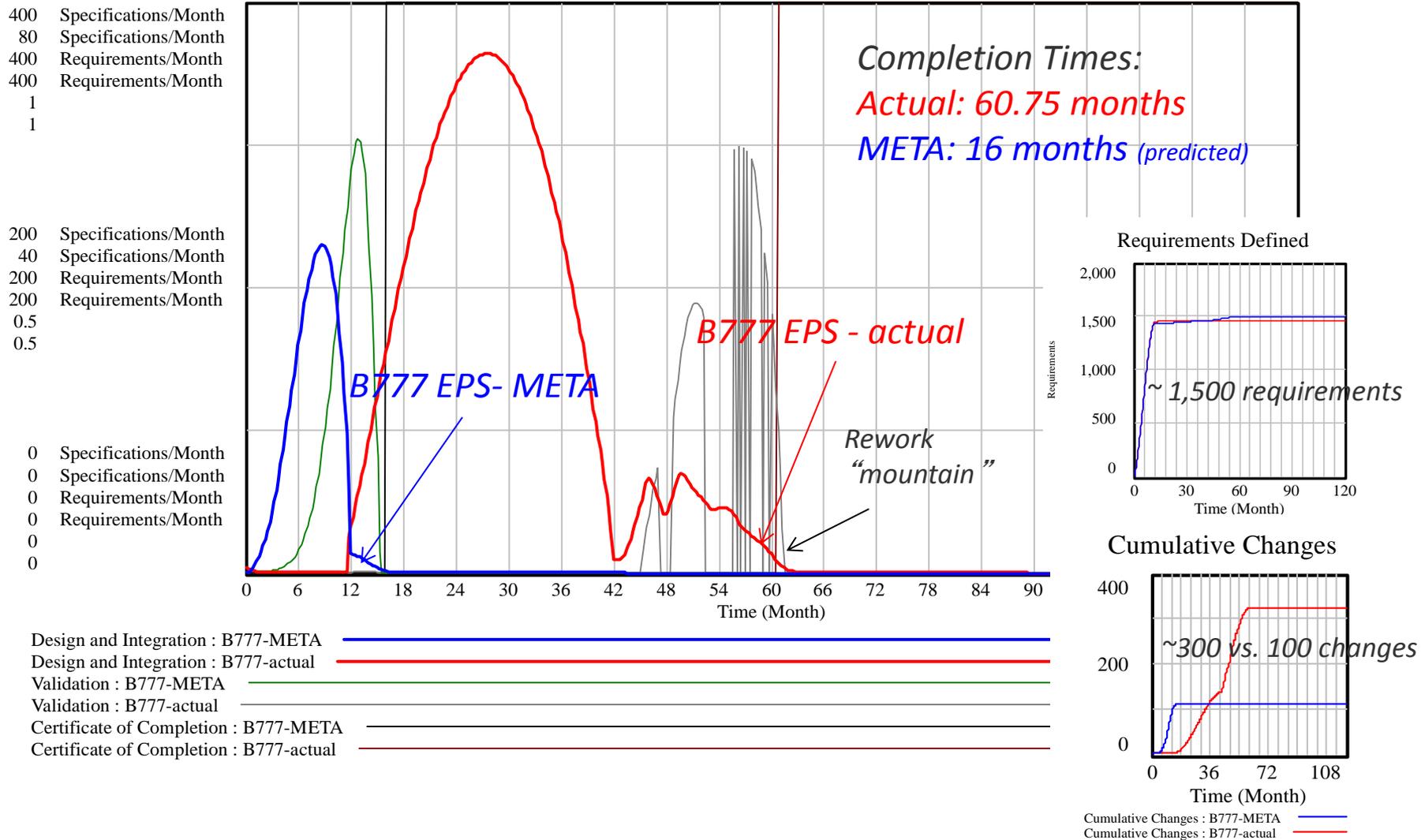


DC and Flight Control Electrical Systems Schematic



# Comparison of B777 EPS Program (actual vs. META)

Comparison B777 - Design and Integration, Validation and Completion



# Summary META (5x) Model

- We are continuing to quantify the schedule and cost impact of the proposed META Design Flow based on a sophisticated Vensim System Dynamics Model:
  - **Speedup factor of 4-5 x seems feasible**
  - Cost improvement is only about 1.5x (w/o cost to build and maintain C2M2L) → META will be much faster but not much cheaper !
- Most important META Design Flow Tool Chain factors are (in order)

META Factor Rank	Schedule Impact for 5x	NRE \$ Cost Impact
1. Most important	Schedule Pressure	Catch problems early
2.	Layers of Abstraction	C2M2L Library Coverage
3.	C2M2L Library Coverage	Schedule Pressure
4. Less important	Catch Problems early	C2M2L Library Integrity

- B777 Electric Power System (EPS) design project was simulated and compared actual (1990-1995) vs. predicted outcome had META been available
  - B777 EPS might have been developed in **16 months (vs. 60)** with META

# What is the current state of SE?

- In 2010 Dr. Mike Griffin wrote a controversial article “**How do we fix Systems Engineering?**”:
  - Organization of characteristics of an “**elegant design**”
  - Current **state of the art in Systems Engineering research** and education and strength of academia-industry interactions



Griffin M.D., “HOW DO WE FIX SYSTEM ENGINEERING?”, IAC-10.D1.5.4, 61st International Astronautical Congress, Prague, Czech Republic, 27 September – 1 October 2010

This image is in the public domain.

“ ... lacking quantitative means and effective analytical methods to deal with the various attributes of design elegance, the development of successful complex systems is today largely dependent upon the intuitive skills of good system engineers.”

“Academic researchers and research teams are rarely, if ever, exposed to the actual practice of system engineering as it occurs on a major development program. Similarly, few if any successful practicing system engineers ... make a transition to academia.”

# Characteristics of an “Elegant Design”

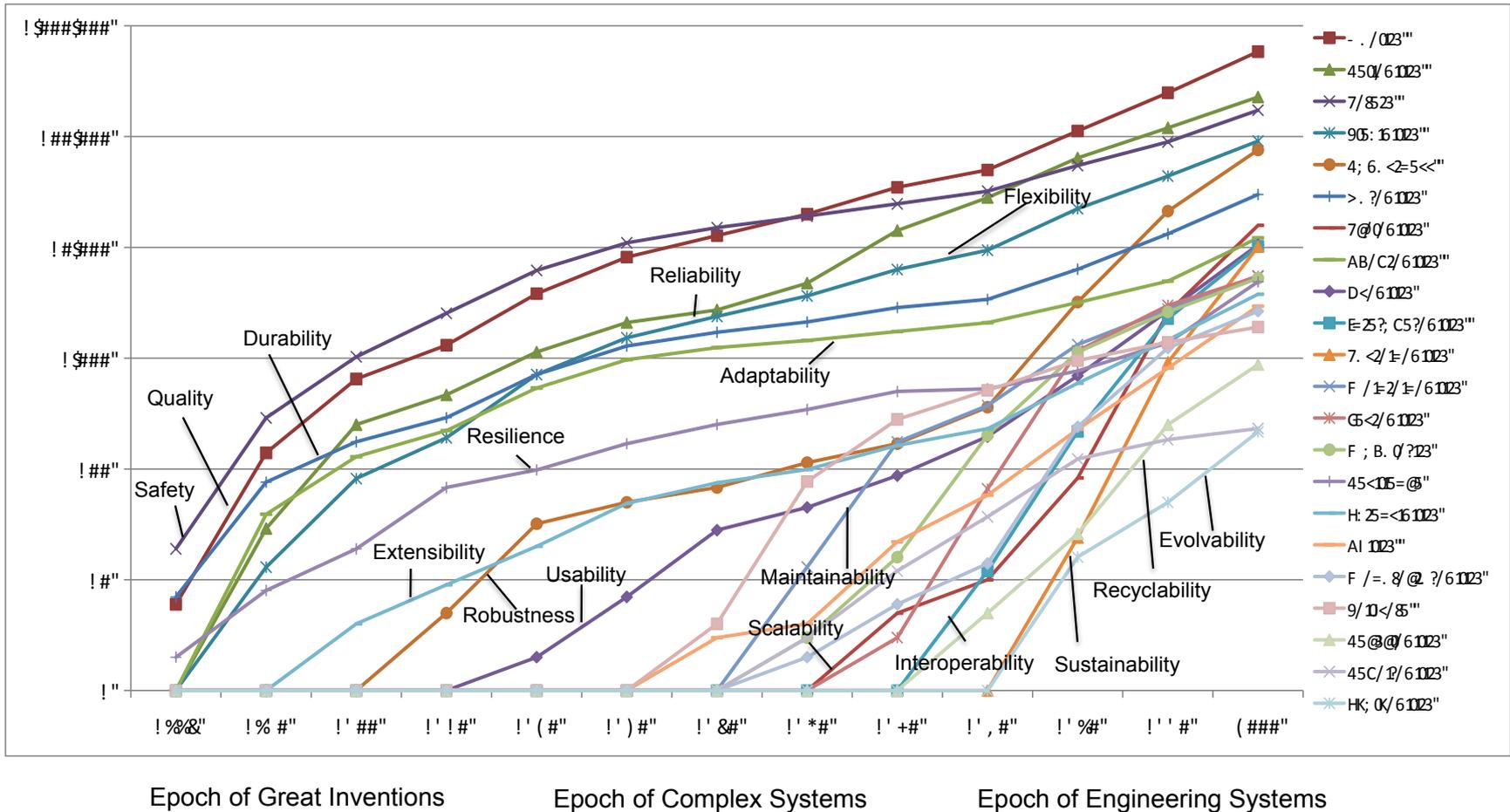


- According to Dr. Griffin
- **Workability** (system produces the anticipated behavior, the expected output)
- **Robustness** (system should not produce radical departures from its expected behavior in response to small changes)
- **Efficiency** (produces the desired result for what is thought to be a lesser expenditure of resources than competing alternatives)
- **Predictability** (accomplishes its intended purposes while minimizing unintended actions, side effects, and consequences)
- According to Dr. de Weck
- **Functional Compliance** (performs the functions we desire at or above the expected level of performance)
- **Simple Architecture** (structural arrangement of the physical parts of form with only essential complexity)
- **Minimal Lifecycle Cost** (including design effort, manufacturing cost, capital expenditures, operating expenses)
- **Superior Lifecycle Properties** (robustness, safety, flexibility to change, maintainability, sustainability ....)

**The main job of the systems engineer is to ensure that these properties are achieved and balanced**

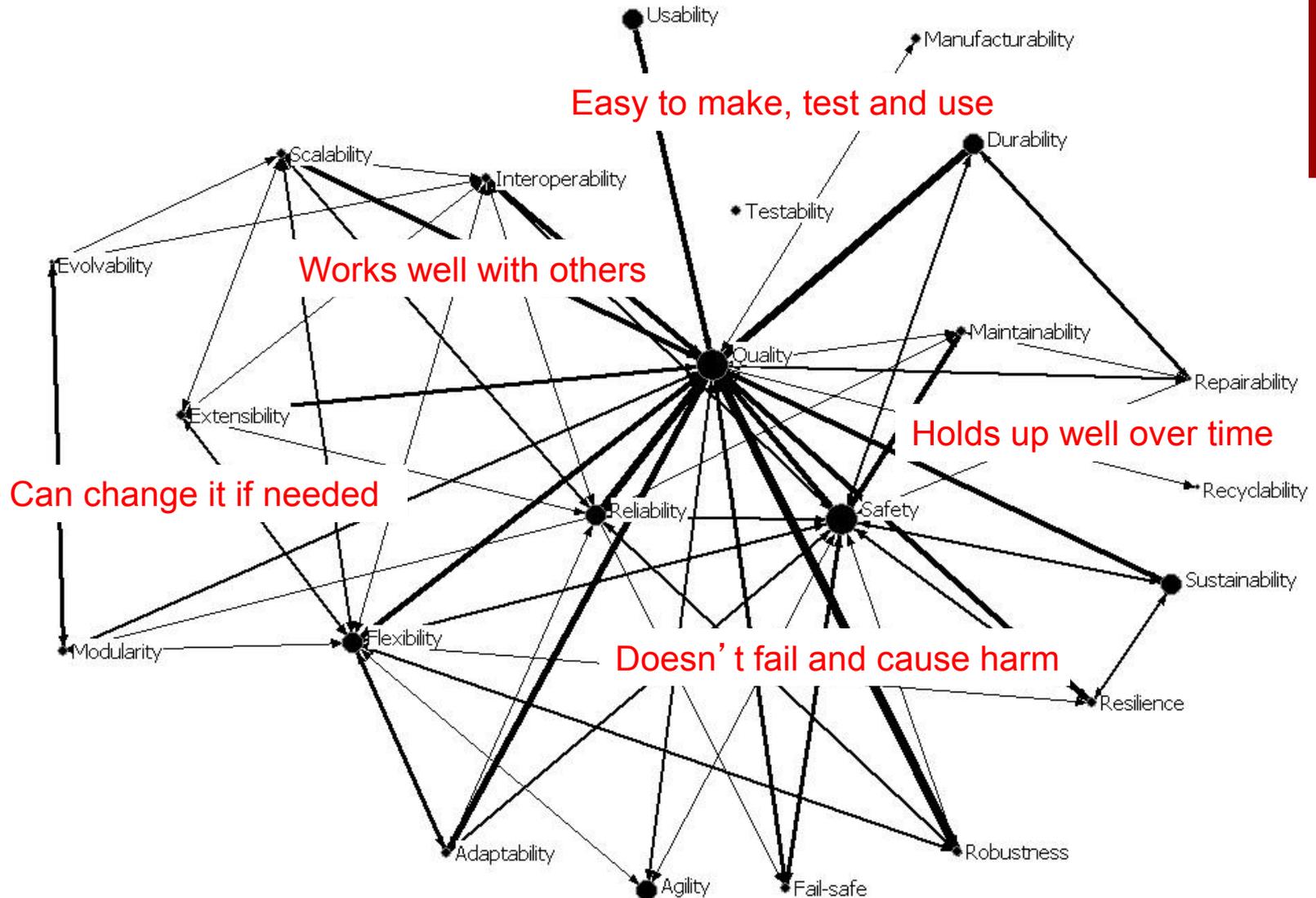
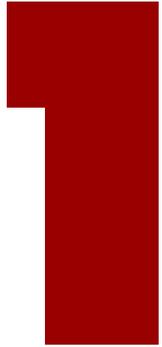
# Importance of Illities over Time

Cumulative Number of Journal Articles published about each Illity



Source: Compendex and Inspec, analysis by O. de Weck, July 2010

# Relationships amongst the Illities



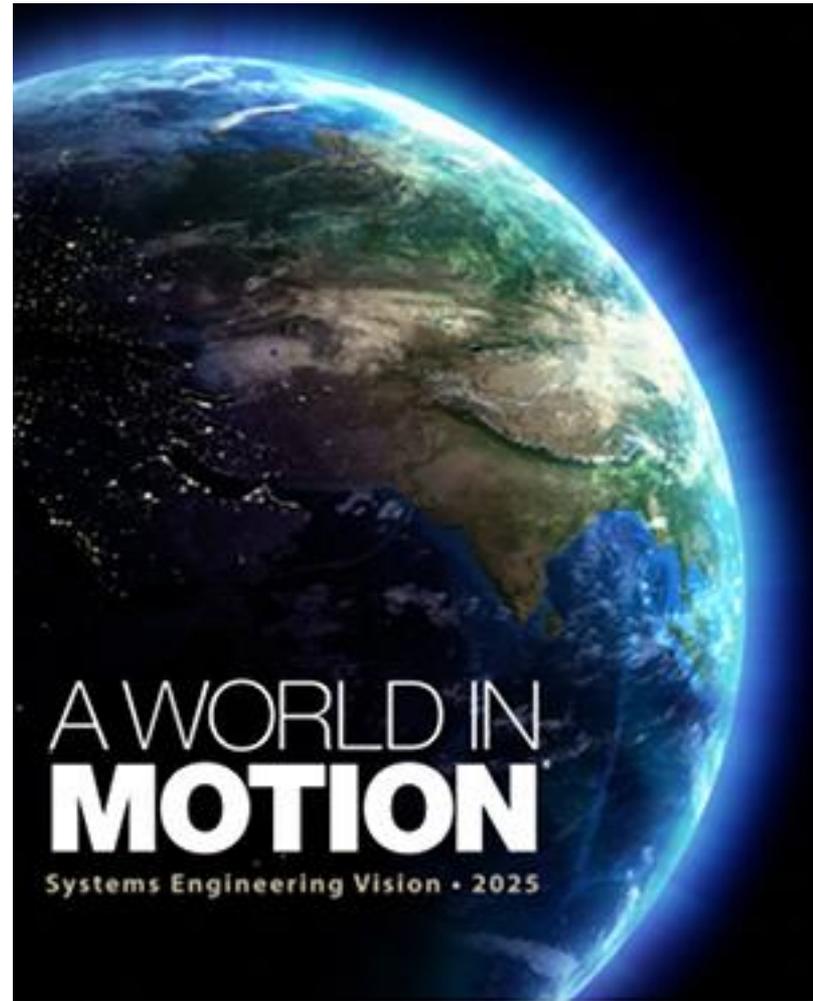
Source: Google keyword 2-tuple correlation analysis, July 2010

# Trends in SE: “Utopia” in 2035

- We design systems with only essential complexity and they don't fail unexpectedly
  - “accidents” may not be preventable altogether but they may be predictable and humans can get out of harms way
- The Technical, Process and Social Layers of the system are co-designed and in harmony with each other
- All system designs are essentially “elegant” and tradeoffs between lifecycle properties are made deliberately
  - Value maximizing sustainable designs are the norm, not the exception
- Projects don't overrun their budgets because rework is eliminated or iterations are included in realistic plans that are accepted by all
- There is a “Nobel Prize” awarded for Systems Engineering or Systems Science
- The 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup> .. Law of systems science and engineering is well established and widely accepted (similar to thermodynamics)

# SE Vision 2025

- Available online at <http://www.incose.org/AboutSE/sevision>



# Final Words

- Thank you for your attention this semester !
- Consider submitting a manuscript to the INCOSE Wiley Journal *Systems Engineering*

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



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