Foundations Work Stream

Technical Complexity Workshop on Monday 30, Jan 2023

Oli de Weck
FuSE Foundations Lead

Agenda.

- Stream Intro (15 min)
  General overview of the SE Foundations stream
- Technical Complexity (45 min)
  Definition of Organizational Complexity and Examples
- Case Study (45 min)
  Aircraft Engines(1950-2020)
- Discussion (15 min)
  Feedback and Q&A related to the topic

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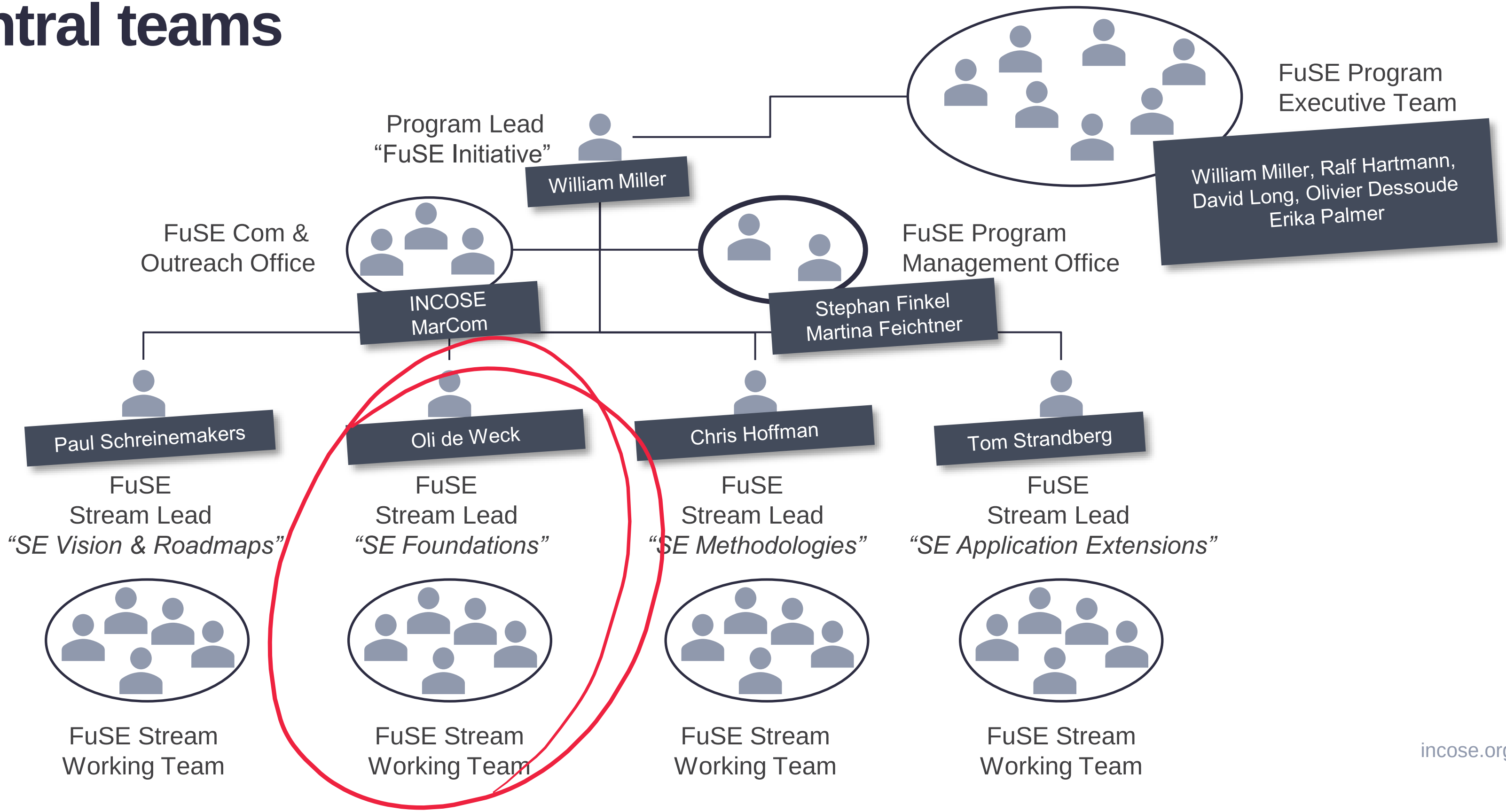
The FuSE program is organized in 4 streams with additional central teams

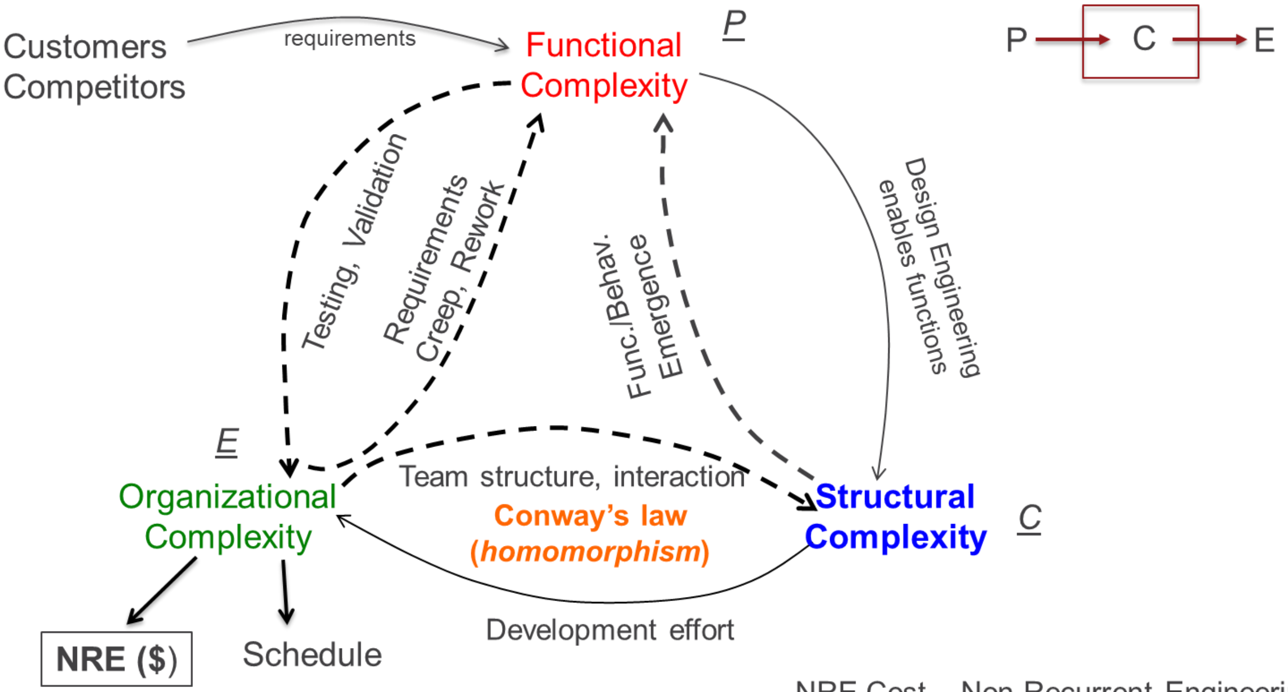


The Foundations Stream's objectives during IW.

The SE Foundations stream aims to:

- Validate (or refute) the proposed First Law of Systems Science and Engineering: **"Conservation of Complexity"**
- Elaborate the drivers of *technical* complexity
- Elaborate the drivers of *organizational* complexity
- Create an *inventory* of existing SE Foundations and tag their status as: (i) proposed, (ii) validated or (iii) adopted in SE practice

Three Dimensions of Complexity in Systems Engineering



NRE Cost – Non-Recurrent Engineering Cost

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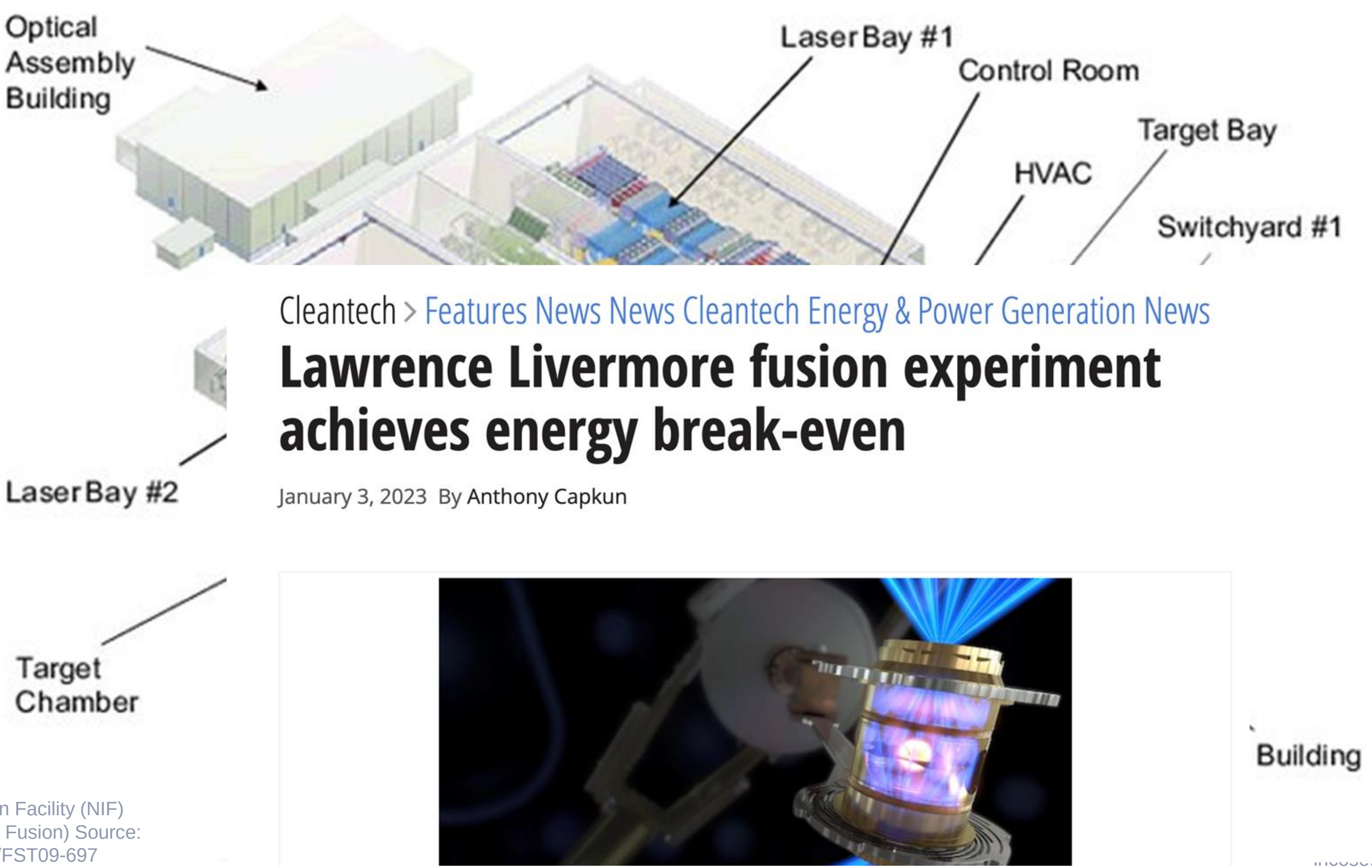


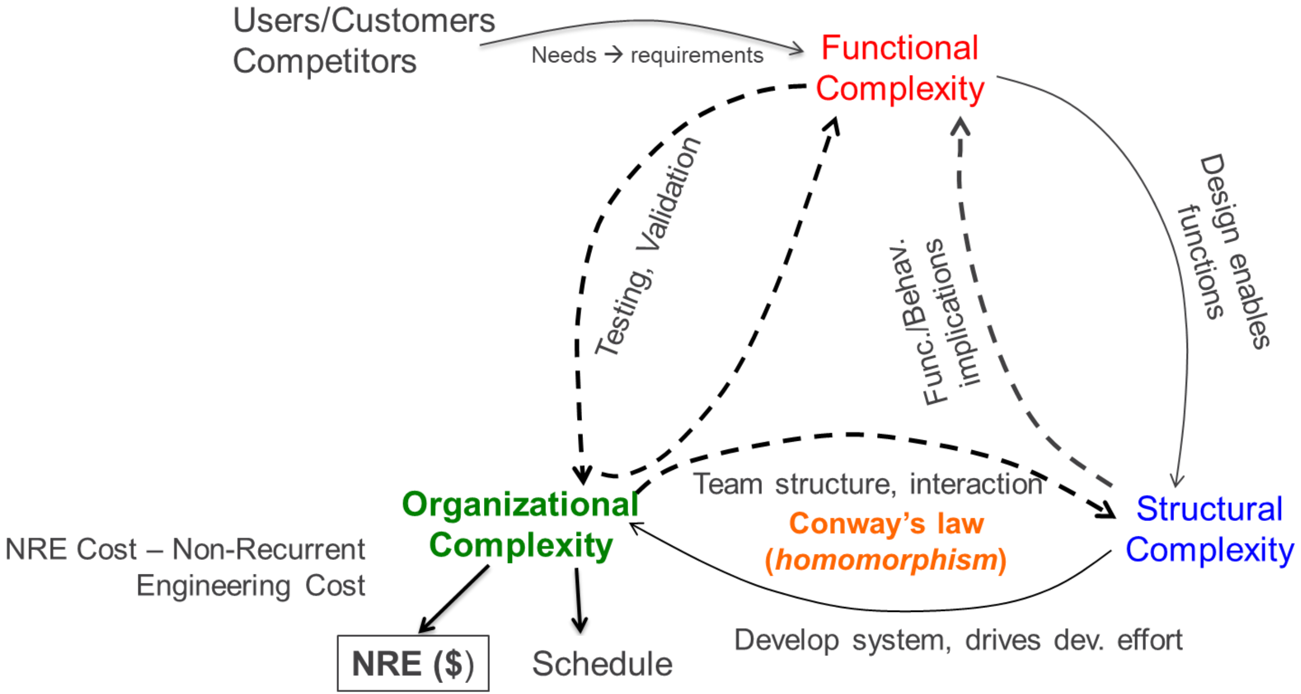
Cleantech > Features News News Cleantech Energy & Power Generation News

Lawrence Livermore fusion experiment achieves energy break-even

January 3, 2023 By Anthony Capkun

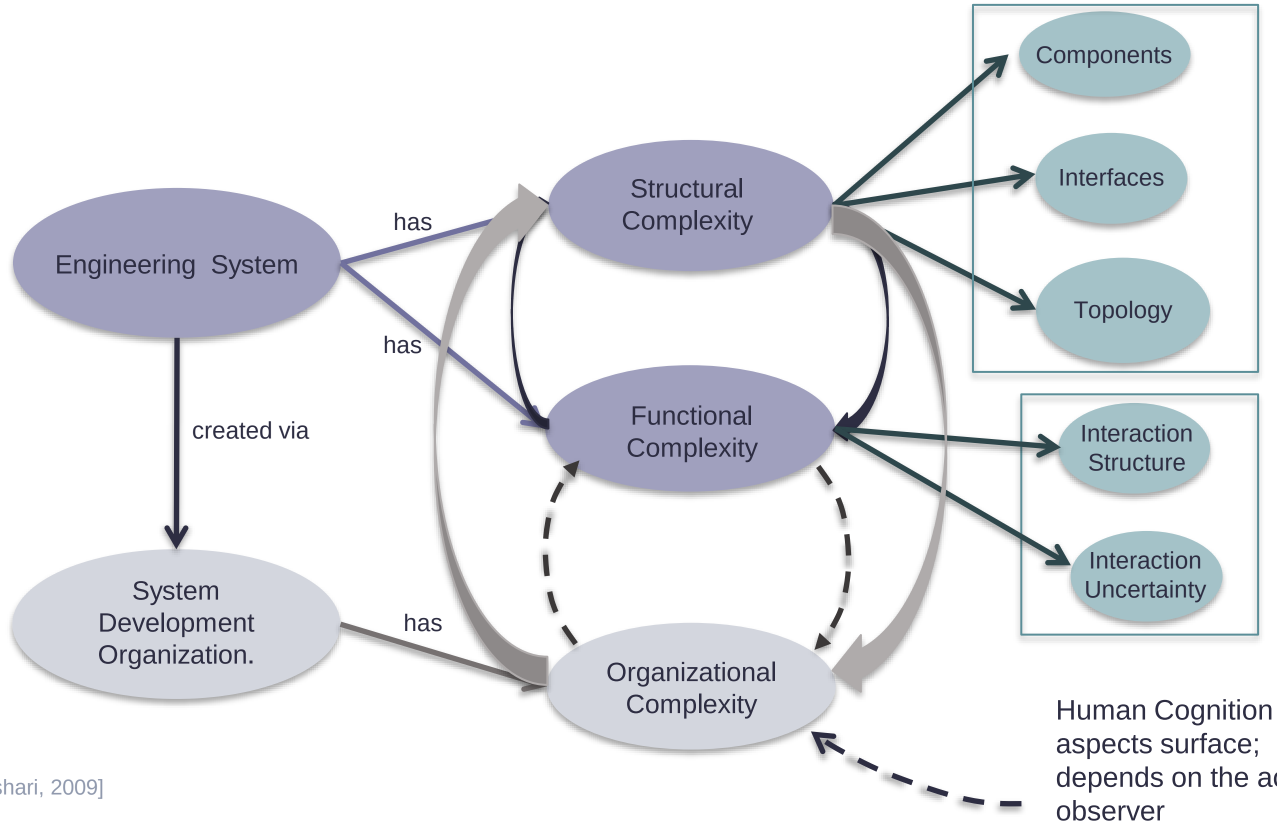
National Ignition Facility (NIF) (Laser Induced Fusion) Source: DOI: 10.13182/FST09-697

Dimensions of Complexity in System Development:



These dimensions of complexity in system development context are positively correlated [Riedl 2000, Lindemann 2009,10, Kreimeyer, 2011]. Technical Complexity reflects the functional and structural elements of the system.

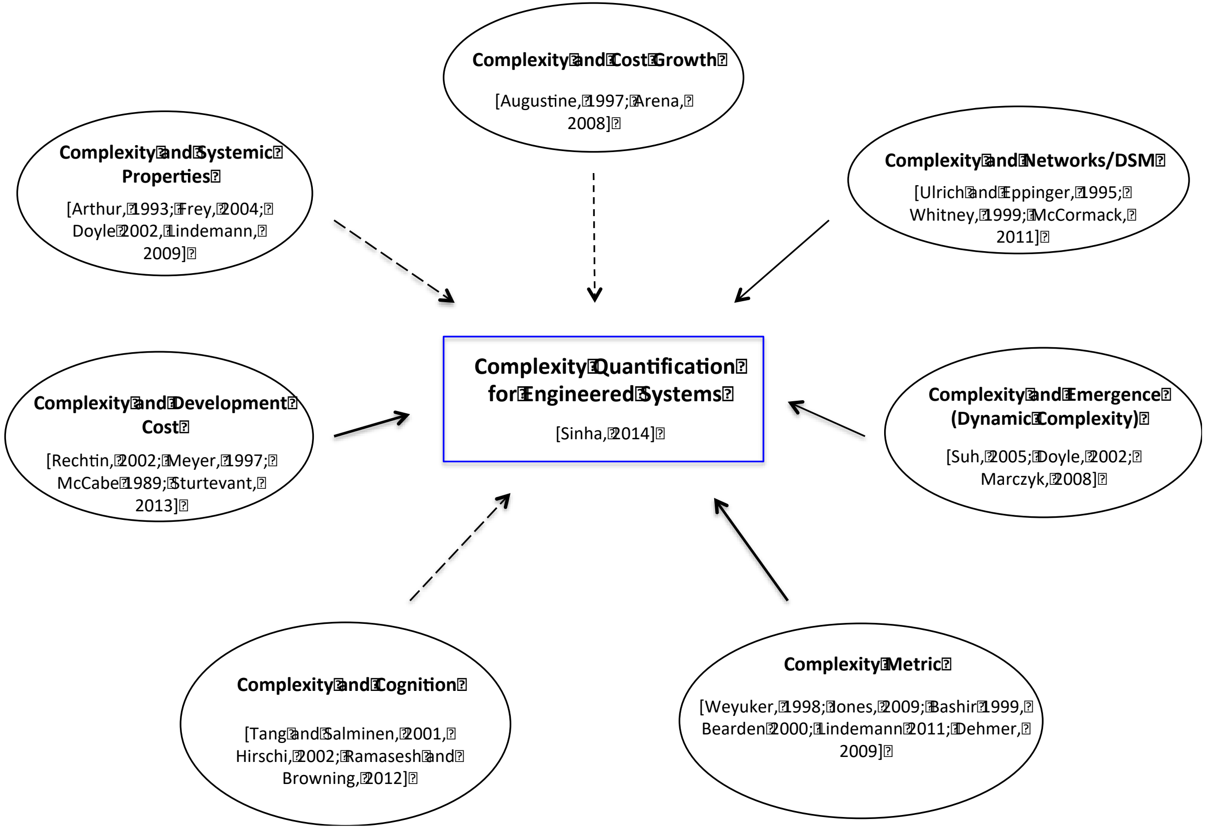
Complexity Typology for Engineered Systems



Human Cognition aspects surface; depends on the actor / observer

[Sheard and Mostashari, 2009]

Relationship with Existing Complexity Literature

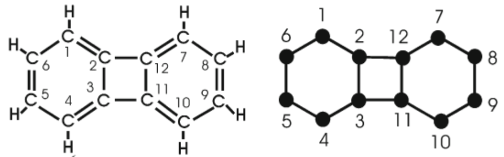


Construct Validity: Weyuker’s Criteria

Graph Energy stands out as both computable and satisfies Weyuker’s criteria and establishes itself as a theoretically valid measure (i.e., construct validity) of complexity.

Complexity Measure	Computability	Aspect emphasized	Weyuker’s Criteria
Number of components [Bralla, 1986]	✔	Component development (count-based measure)	✗
Number of interactions [Pahl and Beitz, 1996]	✔	Interface development (count-based measure)	✗
Whitney Index [Whitney *et al.*, 1999]	✔	Components and interface developments	✗
Number of loops, and their distribution []	✗	Feedback effects	✗
Nesting depth [Kerimeyer and Lindemann, 2011]	✗	Extent of hierarchy	✗
Graph Planarity [Kortler *et al.*, 2009]	✔	Information transfer efficiency	✗
CoBRA Complexity Index [Bearden, 2000]	✔	Empirical correlation in similar systems	✗
Automorphism-based Entropic Measures [Dehmer *et al.*, 2009]	✗	Heterogeneity of network structure, graph reconfigurability	✔
Matrix Energy / Graph Energy	✔	Graph Reconstructabality	✔

System Hamiltonian and Structural Complexity



$$[\mathbf{H}]_{ij} = \begin{cases} \alpha & \text{if } i = j \\ \beta & \text{if the atoms } i \text{ and } j \text{ are chemically bonded} \\ 0 & \text{if there is no chemical bond between the atoms } i \text{ and } j. \end{cases}$$

$$\mathbf{H} = \alpha \begin{bmatrix} 1&0&0&0&0&0&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0&0&0&0&0 \\ 0&0&0&1&0&0&0&0&0&0&0&0 \\ 0&0&0&0&1&0&0&0&0&0&0&0 \\ 0&0&0&0&0&1&0&0&0&0&0&0 \\ 0&0&0&0&0&0&1&0&0&0&0&0 \\ 0&0&0&0&0&0&0&1&0&0&0&0 \\ 0&0&0&0&0&0&0&0&1&0&0&0 \\ 0&0&0&0&0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&0&0&0&0&1 \end{bmatrix} + \beta \begin{bmatrix} 0&1&0&0&0&1&0&0&0&0&0&0 \\ 1&0&1&0&0&0&0&0&0&0&0&1 \\ 0&1&0&1&0&0&0&0&0&0&1&0 \\ 0&0&1&0&1&0&0&0&0&0&0&0 \\ 0&0&0&1&0&1&0&0&0&0&0&0 \\ 1&0&0&0&1&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&1&0&0&0&1 \\ 0&0&0&0&0&0&1&0&1&0&0&0 \\ 0&0&0&0&0&0&0&1&0&1&0&0 \\ 0&0&0&0&0&0&0&0&1&0&1&0 \\ 0&0&1&0&0&0&0&0&0&1&0&1 \\ 0&1&0&0&0&0&1&0&0&0&1&0 \end{bmatrix}.$$

$$H = \alpha I_n + \beta A(G)$$

$$H\psi = \varepsilon\psi$$

$$|\varepsilon_i| = \alpha + \beta\sigma_i; \;\; \varepsilon_\pi = \sum_{i=1}^{n} h_i |\varepsilon_i|$$

$$\varepsilon_\pi = n\alpha + \beta\sum_{i=1}^{n} h_i\sigma_i \le n\alpha + \beta\underbrace{\left(\sum_{i=1}^{n} h_i\right)}_{n}\underbrace{\left(\sum_{i=1}^{n}\sigma_i\right)}_{E(A)}$$

$$\therefore \varepsilon_\pi \le n\alpha + n^2\beta\left(\frac{E(A)}{n}\right)$$

Introduce the notion of *configuration energy*:

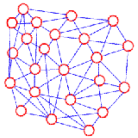
$$\Xi := \underbrace{n\hat{\alpha}}_{C_1} + \underbrace{m\hat{\beta}}_{C_2}\underbrace{\left(\frac{E(A)}{n}\right)}_{C_3} = C_1 + C_2C_3$$

Use the above functional form to measure the complexity associated with system structure – ***Structural Complexity*** of the system where α's stand for component complexity while β's stand for interface complexity:

$$C = C_1 + C_2C_3$$

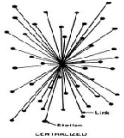
$$= \sum_{i=1}^{n}\alpha_i + \left(\sum_{i=1}^{n}\sum_{j=1}^{n}\beta_{ij}\right)\left(\frac{E(A)}{n}\right) = \sum_{i=1}^{n}\alpha_i + \left(\sum_{i=1}^{n}\sum_{j=1}^{n}\beta_{ij}\right)\gamma E(A)$$

C3 Topological Complexity: Important Properties



"Distributed" Architecture

"Hierarchical" Architecture



Centralized architecture

Simple components / constituents / building blocks with intricate connectivity structure

Higher system integration effort

Increasing Topological Complexity (C_3)

Complex components / constituents / building blocks with simple connectivity structure

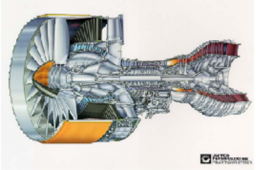
Low system integration effort

Centralized Architecture ! *hypoenergetic*, $C_3 < 1$!!

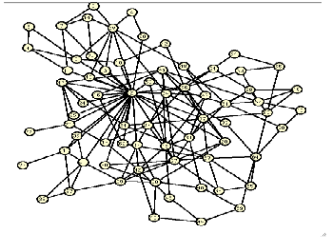
Hierarchical / layered Architecture ! *transitional*, $1 " C_3 < 2$!!

Distributed Architecture ! *hyperenergetic*, $C_3 " 2$!!

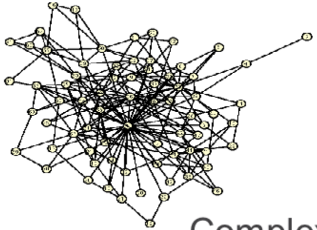
Empirical Data: Complexity Increase of Engines

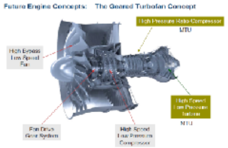


Old



Complexity = 351





New

Complexity = 499

Complexity increase +42%

	C_1		C_2		C_3		C		C/C_{ML}		C_{new}/C_{old}
	Old	New	Old	New	Old	New	Old	New	Old	New	
Most Likely	161	188	126	184	1.51	1.69	351	499	1	1	1.42
Mean	179	244	141	240.4	1.51	1.69	392	650.3	1.12	1.30	1.65
Median	178	242	139	238.9	1.51	1.69	388	646.8	1.10	1.29	1.66
70 percentile	181	247.9	145	246.2	1.51	1.69	399.6	663.94	1.14	1.33	1.66

Trend towards more distributed architecture with higher structural complexity and significantly higher development cost*.

Discussion: Technical Complexity

1. How would you *define* technical complexity?
2. How do you currently *quantify* technical complexity? How should it be done?
3. Has technical complexity *increased* in your domain over time? How much? Why?
4. How would you actively *manage* technical complexity?

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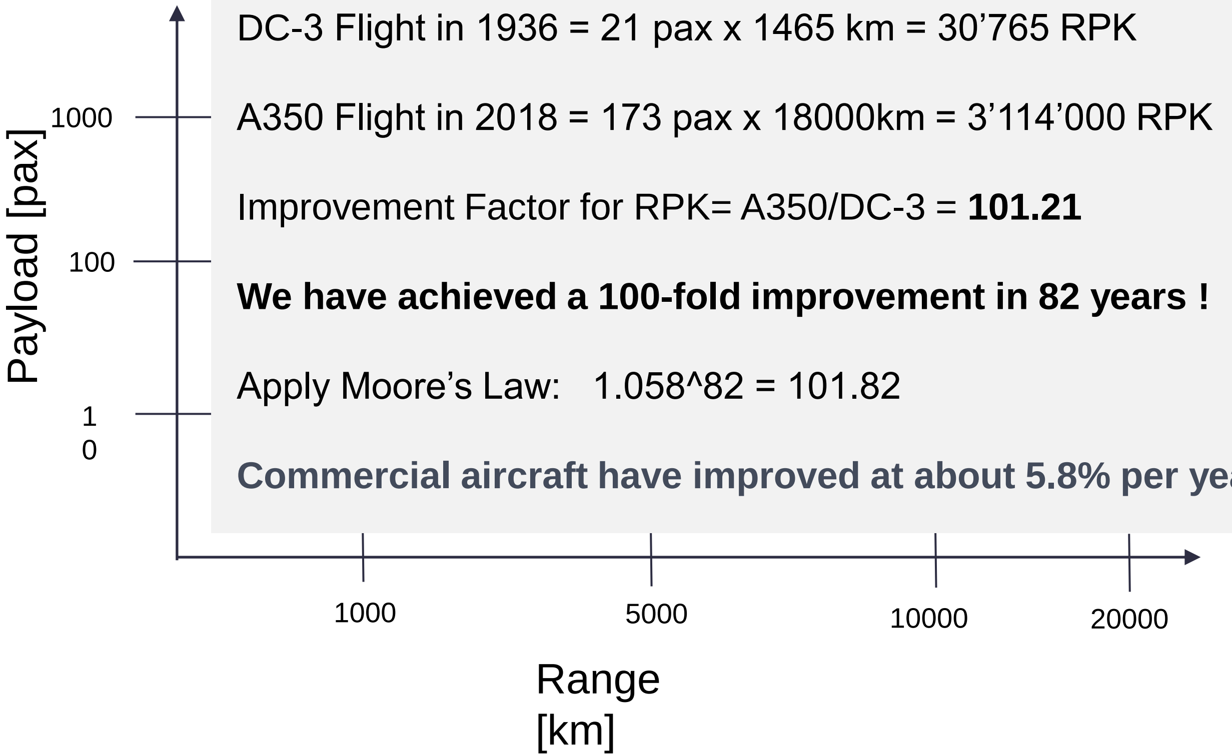
Aviation’s progress over the last 80+ years is impressive



DC-3 Flight in 1936 = 21 pax x 1465 km = 30’765 RPK

A350 Flight in 2018 = 173 pax x 18000km = 3’114’000 RPK

Improvement Factor for RPK= A350/DC-3 = **101.21**

We have achieved a 100-fold improvement in 82 years !

Apply Moore’s Law: 1.058^82 = 101.82

Commercial aircraft have improved at about 5.8% per year

Figures of Merit (FOMs)

Range

Payload

Safety

Operational Reliability

Cash Operating Cost

Aircraft Price

Emissions

Bréguet Range Equation

h : fuel energy per unit mass (specific energy)

g: Earth's average gravity at the surface g=9.81 m/s^2.

L/D: Lift over drag ratio at cruise.

$\eta_{overall}$: Overall efficiency

W_{inital}: Gross takeoff weight of the aircraft

W_{final}: "Final" weight of the aircraft including the dry mass of the aircraft

V: Cruise speed, also denoted as v_∞ or u_o.

SFC: Specific Fuel Consumption: this is the amount o fuel burned per unit time per unit of thrust, i.e. units of [kg/s/N].

fuel energy/mass

propulsion system efficiency

$$Range = \frac{h}{g} \; \frac{L}{D} \; \eta_{overall} \; \ln \frac{W_{initial}}{W_{final}}$$

Earth's gravity acceleration

aerodynamic efficiency

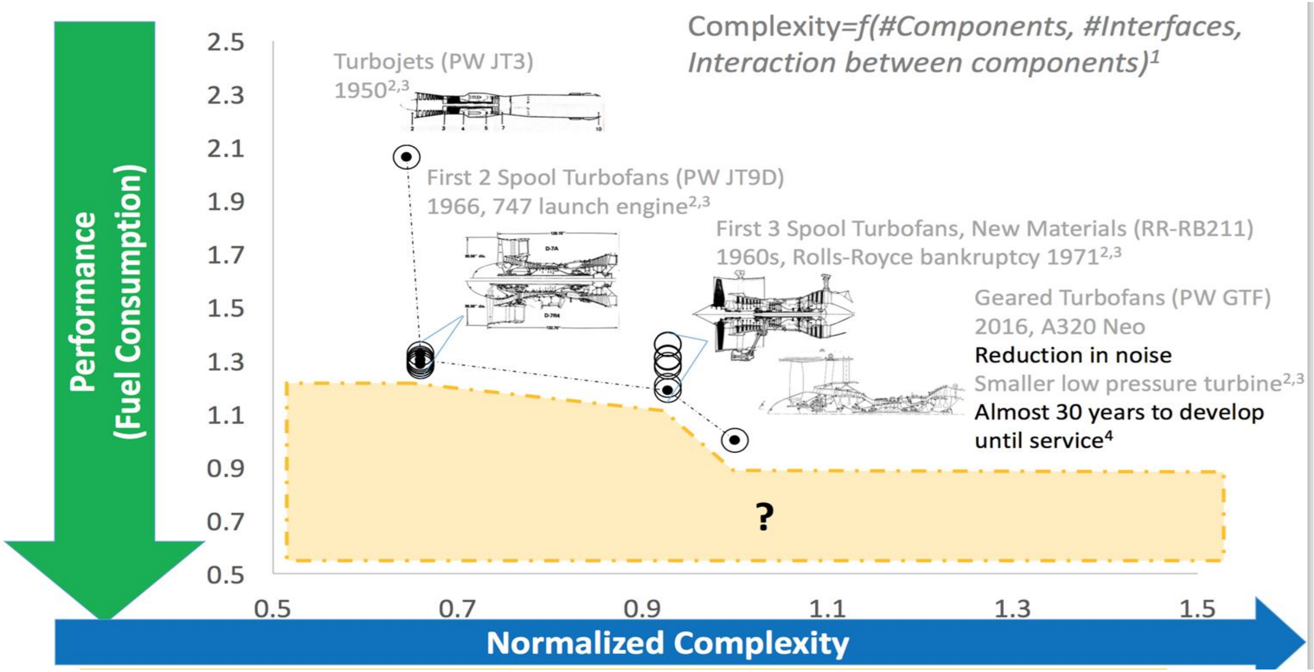
structural weight

Or equivalently,

$$Range = \frac{V \cdot L/D}{g \cdot SFC} \ln\left(\frac{W_{initial}}{W_{final}}\right)$$

where SFC = mass flow of fuel per unit thrust (kg/s/N or lbm/hr/lbf)

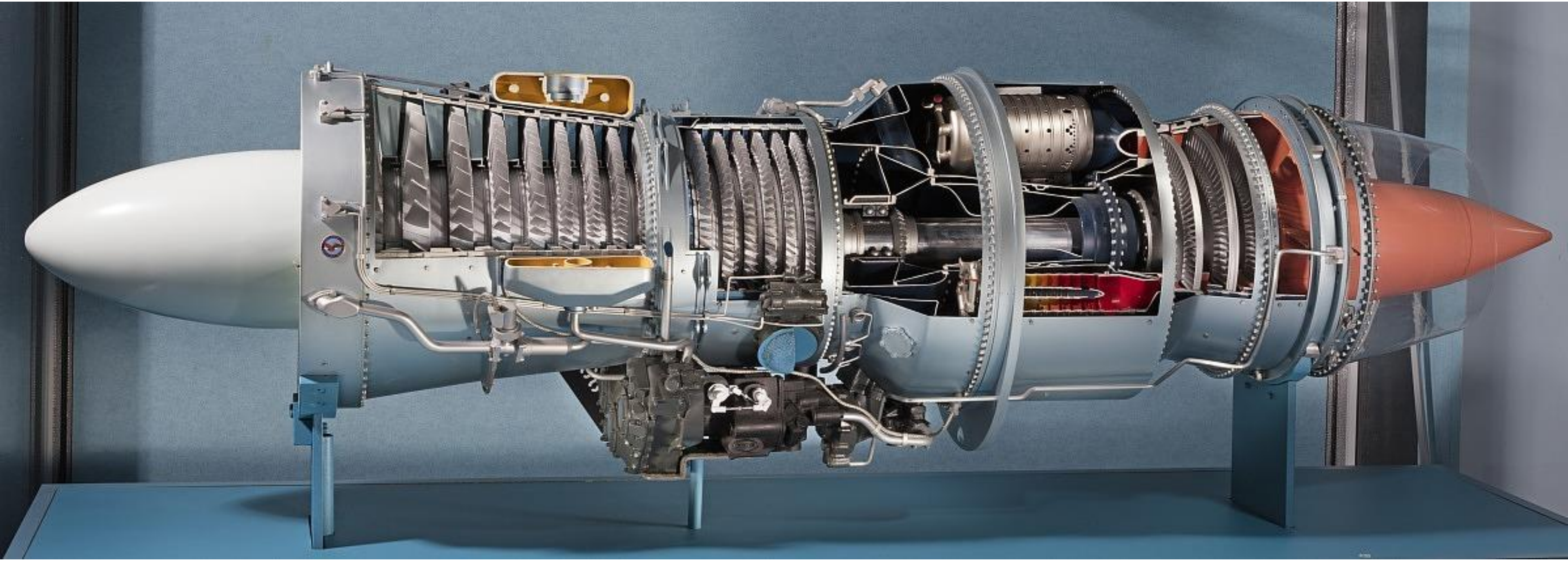
Progress in Engine Technology



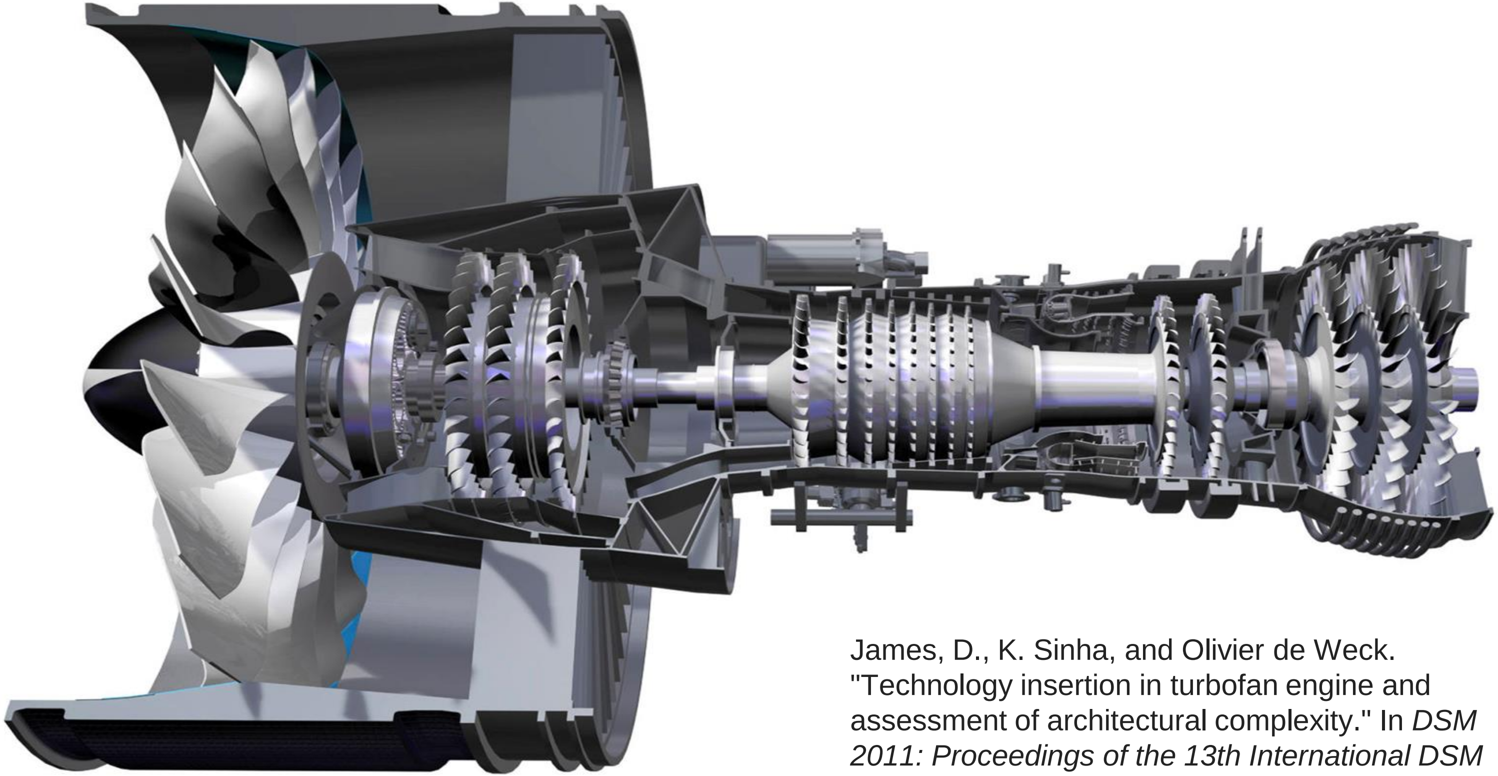
Improvement in Fuel Consumption (SFC) was achieved by increasing complexity

2x improvement since 1950's through:

- Multi-stage compressors and turbines
- High BPR
- Fan-Drive Gear System



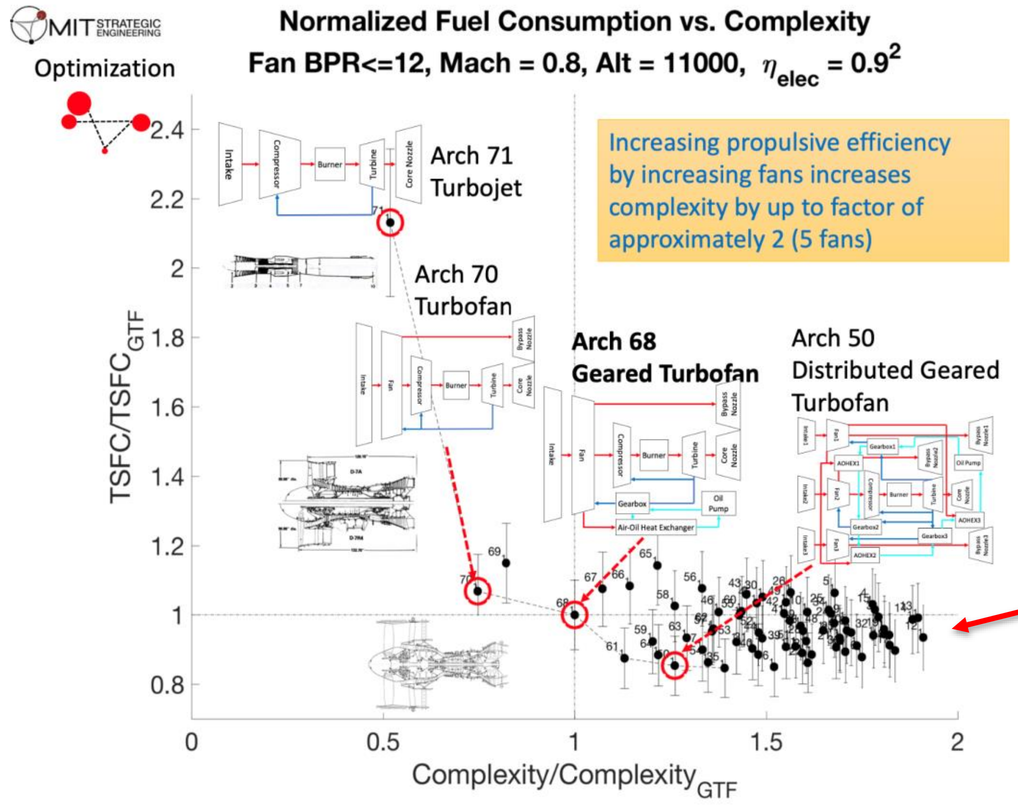
PW JT3 Turbojet Engine 1950



PW-1500 Geared Turbofan Engine
2020

James, D., K. Sinha, and Olivier de Weck. "Technology insertion in turbofan engine and assessment of architectural complexity." In *DSM 2011: Proceedings of the 13th International DSM Conference*. 2011.

Where do we go from here?



Is it worthwhile operating in this zone?

Too much complexity in exchange for performance?

Performance

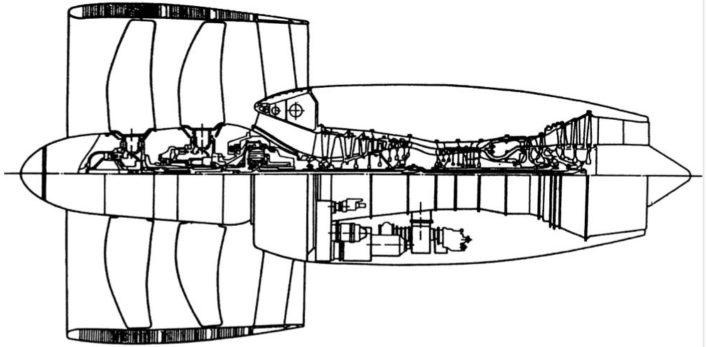
"Most efficient engine ever tested"
Jane's Aero Engines, 2010

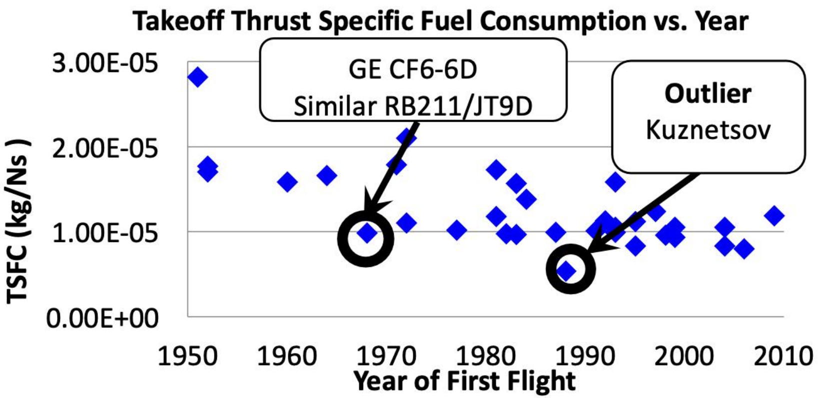
Complexity

Complex, never certified

- 2 counter-rotating variable pitch fans
- Counter-rotating gearboxes
- 3 spools

Kuznetsov NK-93/94:





Discussion: Case Study Engines

1. Do you think aircraft jet engines have reached the “maximum value” point of complexity?
2. How will electric propulsion or hydrogen change the equation (next S-Curve)?
3. What other case studies would you propose to map the evolution of technical complexity over time?
4. How can (MB)SE be used to better manage complexity?

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Session Wrap-up: Technical Complexity

- **Part 1:** Definition and quantification of technical complexity
- **Part 2:** Case Study: Aircraft Engines
- Inputs from all groups will be collected and summarized in a white paper, which will be provided to participants

FuSE at IW 2023 overview

	SAT	SUN	MON	TUE
08:00		FuSE Stream Working Sessions 4 rooms (in person only)	FuSE Stream Working Sessions 4 rooms (in person only)	
08:30				Wrap-up FuSE (for participants)
09:00				
09:30	Break			
10:00	FuSE Kick-off	Break		
10:30				
11:00				Wrap-up FuSE
11:30				
12:00	Lunch			
12:30				
13:00				
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15:00	Break			
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16:00				
16:30				

Rooms for FuSE Stream Sessions:
Vision & Roadmaps Stream: Ballroom
Foundations Stream: Salon A
Methodologies Stream: Salon D
Application Extensions Stream: Salon C

Systems Engineering Foundations Stream

Oli de Weck
Stream Lead “SE Foundations”

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In order to yield predictable results Systems Engineering methods and tools need to be built on foundational principles that are provably true and based on laws and axioms that can be tested for falsifiability similar to those in other well-established disciplines of science and engineering like Chemical Engineering, Electrical Engineering or Biological Engineering. This stream will formulate a set of candidates underlying Laws of Systemics, the science at the foundation of Systems Engineering.

The IW 2023 goal is to assess the foundational value of the “Conservation of System Complexity,” which parallels the Conservation of Energy in the First Law of Thermodynamics and the Conservation of Mass in continuum mechanics.

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Systems Engineering Foundations Stream

Oli de Weck
Stream Lead “SE Foundations”

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16:00				
16:30				

IW PLAN

Tuesday – FuSE Wrap-up Session (Bill Miller)

Let's connect.

Or find us on www.incose.org/fuse

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