Foundations Work Stream

Organizational Complexity Workshop on Sunday 29 Jan 2023

Oli de Weck
FuSE Foundations Lead

Agenda.

- Stream Intro (15 min)
  General overview of the SE Foundations stream
- INCOSE Systems Science WG (45 min)
  Overview of the INCOSE SSWG and Foundations Established to date
- Organizational Complexity (30 min)
  Definition of Organizational Complexity and Examples
- Case Study (15 min)
  SLS vs. Falcon 9
- Closure

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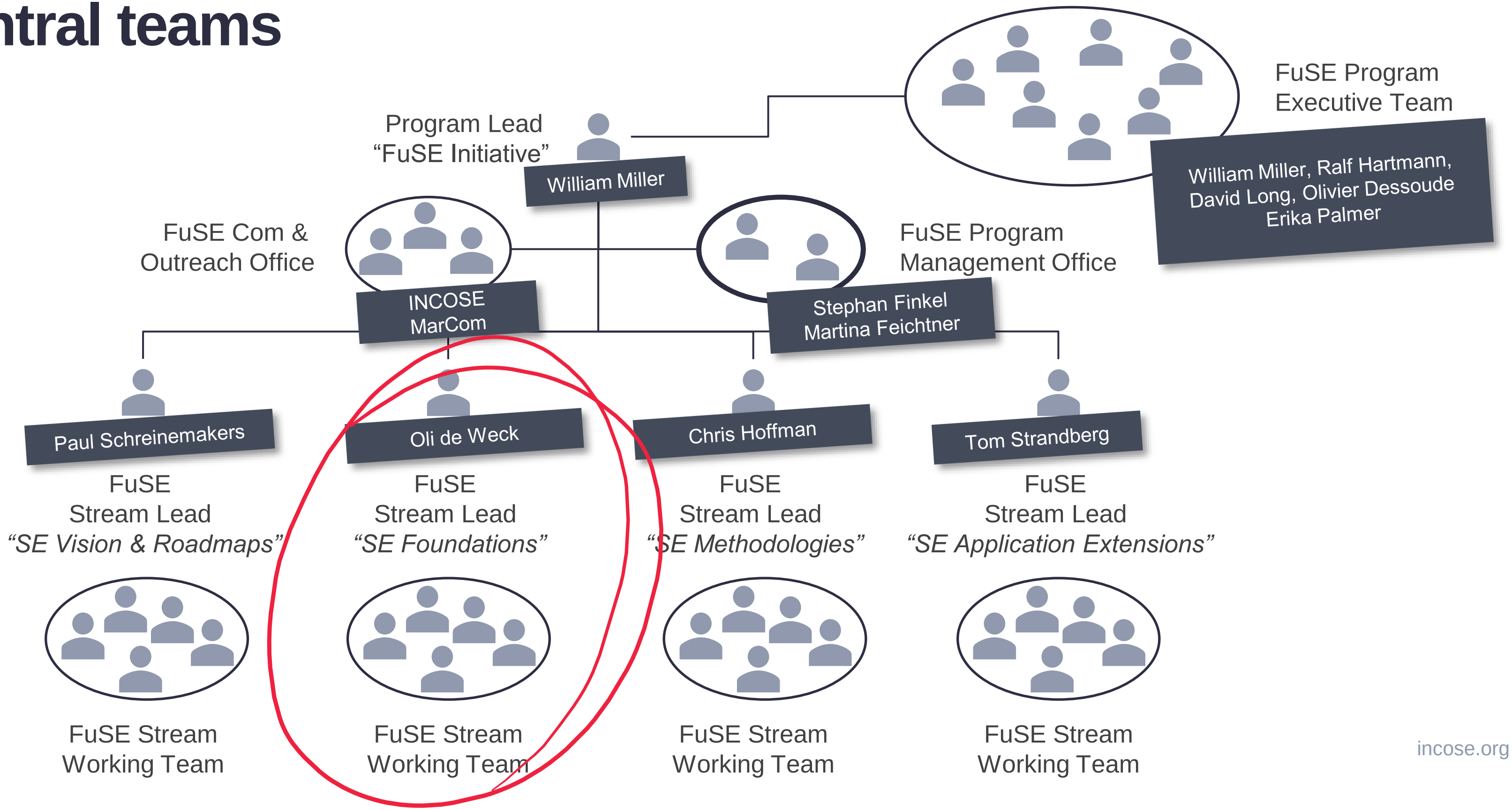
The FuSE program is organized in 4 streams with additional central teams

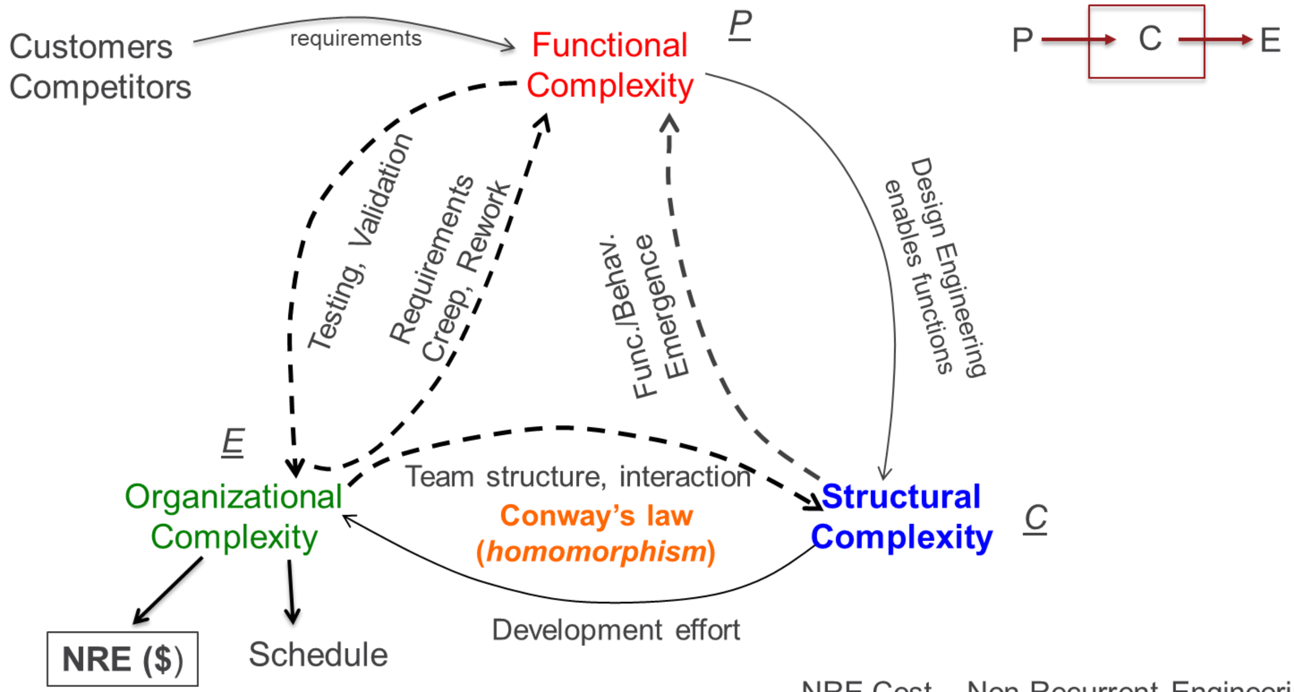


The Foundations Stream's objectives during IW.

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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INCOSE Systems Science WG

Javier Calvo-Amodio, Ph.D., F.ASEM (He/Him) · 2nd
Associate Professor, Industrial Engineering at Oregon State University | Chair, Systems Science Working Group, INCOSE | Deputy Editor, Systems Research and Behavioral Science Journal | VP Research and Publications, ISSS
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Systems Science Working Group

Mission & Objectives

Promote the advancement and understanding of Systems Science, Systems Theories and their application to SE.

We have the following objectives:

- Encourage advancement of Systems Science principles and concepts as they apply to Systems Engineering.
- Promote awareness of Systems Science as a foundation for Systems Engineering.
- Highlight linkages between Systems Science theories and empirical practices of Systems Engineering.

Systems science provides a rigorous, underlying basis to the empirically derived practices to systems engineering that have evolved over time.

Discussion

- Are you aware of Systems Science as a field of research and practice? How would you describe the maturity of this field?
- What is the difference between axioms, laws, principles, and heuristics? Does it matter? How does it apply to SE?
- Please write down 5 things that you consider as foundational (existing or potential) for the work done in and by Systems Engineering. Please classify these as either:
  i) proposed, (ii) validated and/or (iii) adopted

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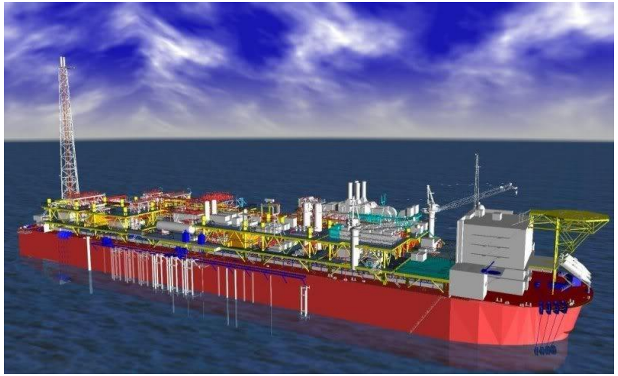
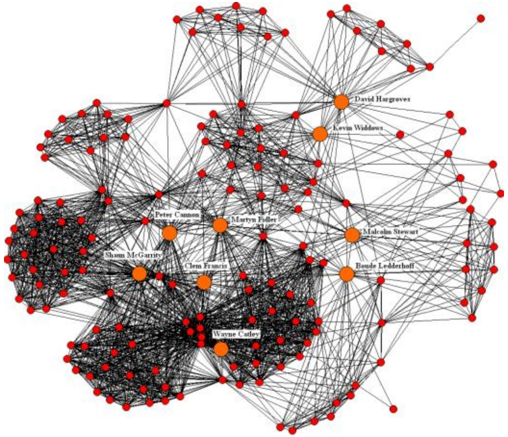
Example: Organizational Complexity

- Large offshore oil and gas project (BP) Angola (Greater Plutonio – Block 18)
- Organizational Network revealed through formal relationships in the Management of Change (MOC) process
- Over 500+ individuals involved
  Some multi-disciplinary engineers hold the network together

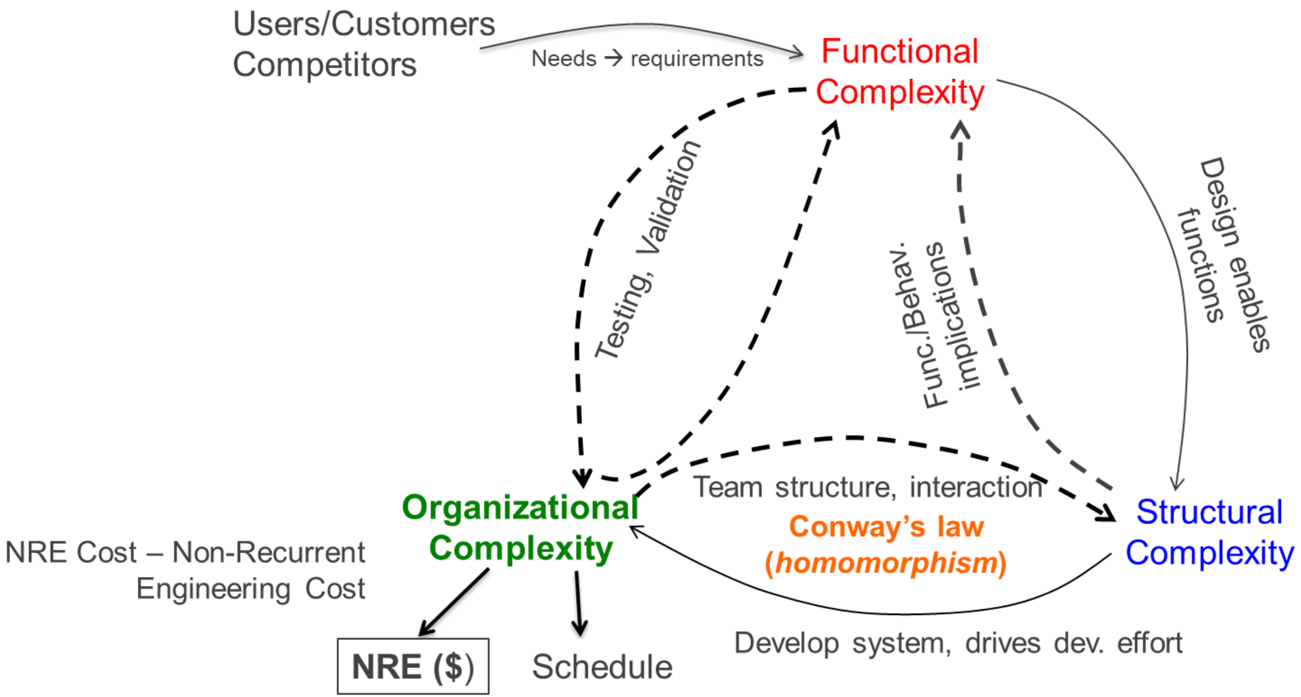




Change owners owning **more than 2 disciplines** in the Greater Plutonio change owner network act as “hubs” in the MOC system

Siddiqi, A., Bounova, G., de Weck, O. L., Keller, R., and Robinson, B. (October 18, 2011). "A Posteriori Design Change Analysis for Complex Engineering Projects." ASME. *J. Mech. Des*. October 2011; 133(10): 101005. https://doi.org/10.1115/1.4004379

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.

Conway’s Law

- Conway’s Law states that the architecture of a product tends to reflect the structure of the organization that developed it.
  - This is also known as a “homomorphism”
  - It has also been dubbed the “mirroring hypothesis”

Dr. Conway is manager, peripheral systems research, at Sperry Rand’s Univac Div., where he is working on recognition of continuous speech. He has previously been a research associate at Case Western Reserve Univ., and a software consultant. He has an MS in physics from CalTech and a PhD in math from Case.

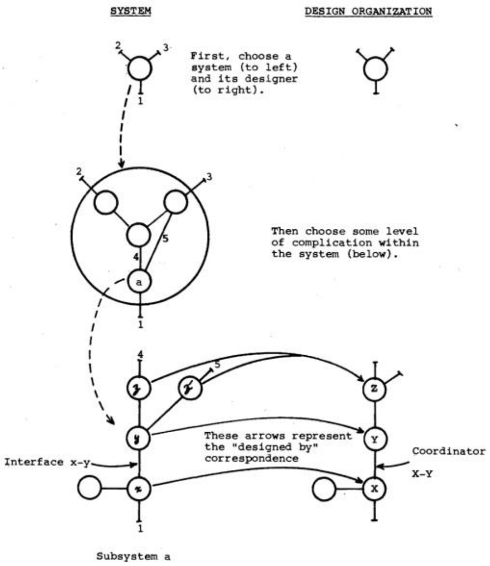
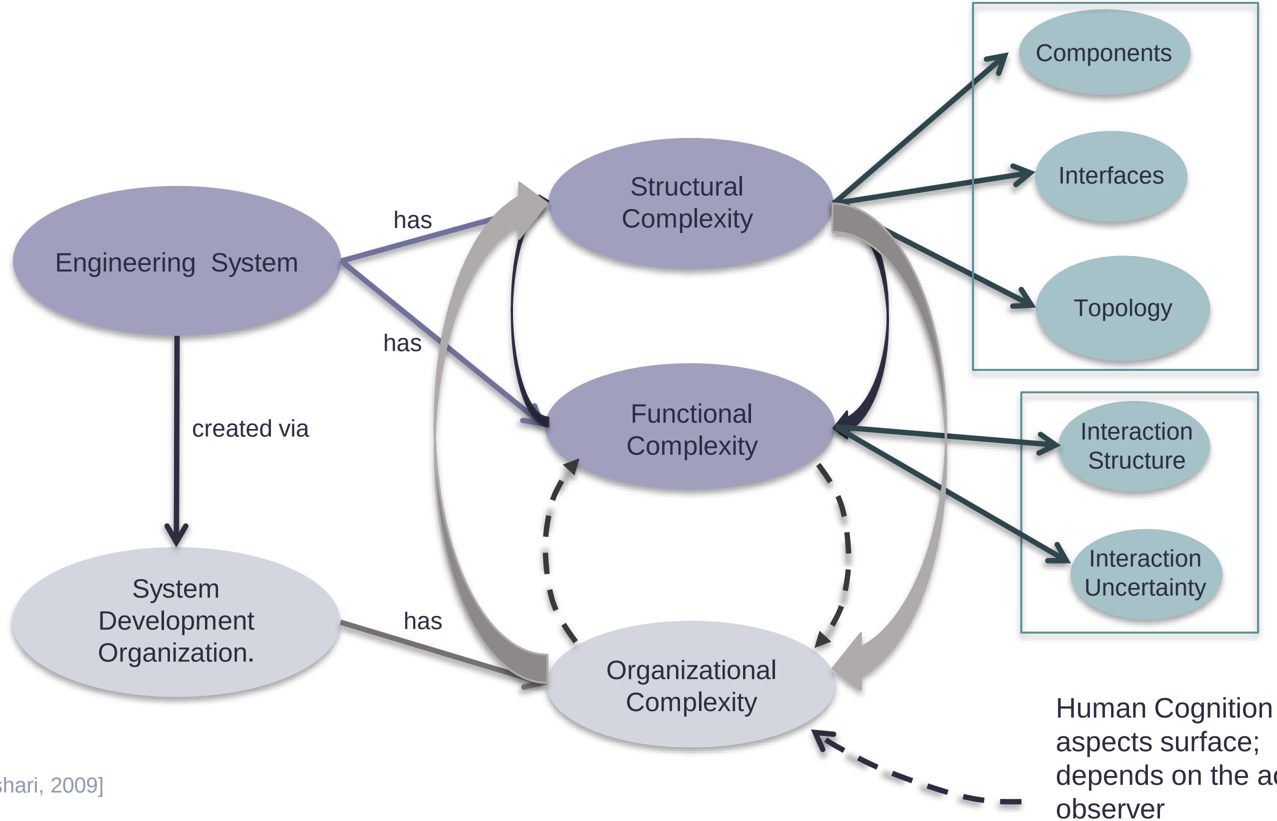


Figure 2 Here is an illustration of the strong relationship between the structure (graph) of a system (left) and the structure of the organization which designed it (right).

Conway, Melvin E. (April 1968). "How do Committees Invent?". Datamation. 14 (5): 28

Complexity Typology for Engineered Systems



Human Cognition aspects surface; depends on the actor / observer

[Sheard and Mostashari, 2009]

Discussion: Organizational Complexity

1. How would you *define* organizational complexity?
2. How do you currently *quantify* organizational complexity? How should it be done?
3. Has organizational complexity *increased* over time? What are the drivers of organizational complexity?
4. How would you actively *manage* organizational complexity? What is the role of methods and tools during product and system development?

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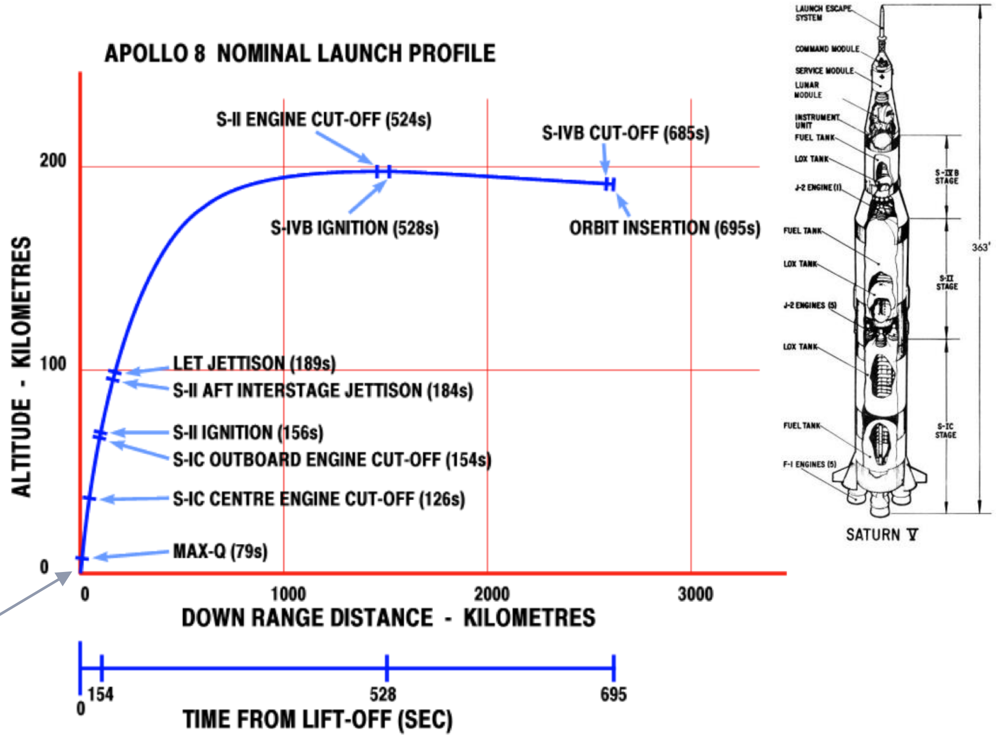
Launch Nominal Profile

- Example: Apollo 8
- Total: about 11.5 min
- LEO: ~ 200 km orbit

$$q = \frac{1}{2}\,\rho\,v^2$$

dynamic pressure



Results are expected to be stochastic given the inherent variability of human performance

TSTO Launch Vehicle Optimization

Name	Symbol	Unit	Description
Objectives			
payload mass	m_p	[kg]	objective
cost	C	[$]	objective
Constraint Outputs			
ending altitude	A_{final}	[km]	constraint
axial mode freq.	ν_a	[Hz]	constraint
bending mode freq.	ν_b	[Hz]	constraint
Design Vector			
initial wet mass	m_0	[kg]	design variable
rocket radius	R_r	[m]	design variable
cone half-angle	θ_c	[rad]	design variable
thrust profile	$T_1 \ldots T_5$	[N]	design variable
angle profile	ca_1, ca_2	-	design variable
staging altitude	A_{stage}	[km]	design variable
fuel type – stage 1		-	design variable
fuel type – stage 2		-	design variable
structure material		-	design variable
tank material		-	design variable
Rocket Dimensions			
length	L_r	[m]	dependent
thickness	t_r	[m]	dependent
cone height	L_c	[m]	dependent

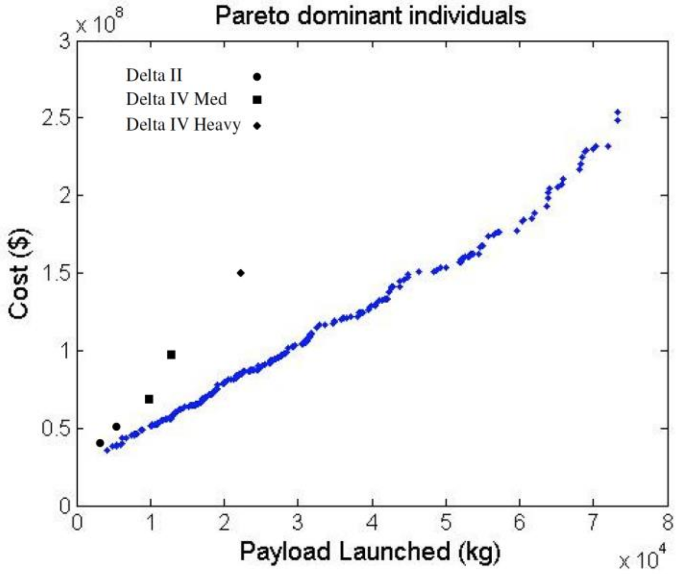


Figure 3-8. Non-dominated points from 1640 MOGA runs with sample rockets plotted[15]

Bairstow, Brian, Olivier de Weck, and Jaroslaw Sobieszczanski-Sobieski. "Multiobjective Optimization of Two-Stage Rockets for Earth-To-Orbit Launch." In 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference 14th AIAA/ASME/AHS Adaptive Structures Conference 7th, p. 1720. 2006.

Falcon-9 FT

- Falcon-9 is developed and manufactured by SpaceX using a vertically integrated organization
- Commercially led
- 178 Launches (FT)
- 0 Failures
- Cost per launch $67M
- Capacity to LEO: 22,800 kg
- Cost per kg: ~$3k
- Schedule: 2005-2010 (5y)
- NRE (v1.0): $300M (vs. $4B* had it been cost-plus)

Source: https://en.wikipedia.org/wiki/Falcon_9_Full_Thrust

Manufacturer	SpaceX
Country of origin	United States
Cost per launch	New: US$67 million (2022)[1] Reused: US$50 million? (2019)[2]
Size	
Height	**FT**: 70 m (230 ft)[3] **v1.1**: 68.4 m (224 ft)[4] **v1.0**: 54.9 m (180 ft)[5]
Diameter	3.7 m (12 ft)[3]
Mass	**FT**: 549 t (1,210,000 lb)[3] **v1.1**: 506 t (1,116,000 lb)[4] **v1.0**: 333 t (734,000 lb)[5]
Stages	2
Capacity	
Payload to Low Earth orbit (LEO)	
Orbital inclination	28.5°
Mass	**FT**: 22.8 t (50,000 lb)[1] Expended 16.7 t (37,000 lb)[6] when landing on ASDS **v1.1**: 13.1 t (29,000 lb)[4] **v1.0**: 10.4 t (23,000 lb)[5]

SLS

- The Space Launch System (SLS) is developed and manufactured by a large consortium in a horizontal distributed organization
- Government-led
- 1 Launch so far (8 planned)
- Cost per launch: $2B
- Capacity to LEO: 95,000 kg
- Cost per kg: ~$21k
- Schedule: 2011-2022 (11y)
- NRE: $27.5B (FY 2022)

SLS launches 4x more mass than F9, but costs 7x more on a per unit mass basis, cost 90x more to develop and took twice as long, why?

Manufacturer	Aerojet Rocketdyne Northrop Grumman Boeing United Launch Alliance
Country of origin	United States
Project cost	US$23.8 billion nominal ($27.5 billion inflation adjusted to 2022) [note 1]
Cost per launch	Over US$2 billion excluding development (estimate) [note 2][2][3]:23–24[4][1]
Cost per year	US$2.555 billion for FY 2021[5]
Size	
Height	**Block 1 Crew:** 322 ft (98 m) **Block 2 Cargo:** 365 ft (111 m)
Diameter	27.6 ft (8.4 m), Core stage [6] 16.7 ft (5.1 m), ICPS [7]
Mass	5,750,000 lb (2,610 t)[8]
Stages	2
Capacity	
Payload to LEO [note 3]	
Mass	**Block 1**: 209,000 lb (95 t)[10] **Block 1B**: 231,000 lb

Discussion: Case Study Launchers

1. What are the virtues and demerits of vertically integrated versus distributed horizontal organizations?
2. How can the organizational complexity of F9 (SpaceX) and SLS (Boeing et al.) be quantified and compared?
3. What is your estimate for % of effort (E) that goes into technical work versus coordination in each organization?
4. To what extent is it possible – using rigorous systems science (first law?) - to predict project outcomes?

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Session Wrap-up: Organizational Complexity

- **Part 1:** Overview Systems Science Working Group (SSWG)
- **Part 2:** Definition and quantification of organizational complexity
- **Part 2:** Case Study: Falcon-9 vs. SLS
- 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				
13:30				
14:00	FuSE Stream Working Session 4 rooms (in person only)			
14:30			B	
15:00	Break			
15:30	FuSE Steam Working Session 4 rooms (in person only)			
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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14:00	FuSE Interactive working session Conduct complexity experiment Frame SE Foundations			
14:30		Break		
15:00	Break			
15:30	FuSE Interactive working session Conduct complexity experiment Frame SE Foundations			
16:00				
16:30				

Systems Engineering Foundations Stream

Oli de Weck
Stream Lead "SE Foundations"

e deweck@mit.edu

In order to yield predictable r… Engineering methods and to… on foundational principles tha… and based on laws and axio… tested for falsifiability similar… well-established disciplines … engineering like Chemical E… Engineering or Biological En… stream will formulate a set … underlying Laws of Systemi… foundation of Systems Engi…

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16:00				
16:30				

IW PLAN

Monday – Dedicated to Organizational Complexity

- Overview of existing Foundations (Systems Science Working Group): Collect inventory of SE Foundations from Audience
- Case Study: NASA SLS vs SpaceX Falcon9
- 8AM-10AM – Discussion

Tuesday – FuSE Wrap-up Session (Bill Miller)

Let’s connect.

Or find us on www.incose.org/fuse

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The FuSE Program is organized in 4 streams.

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