Systems Engineering Foundations Stream Introduction

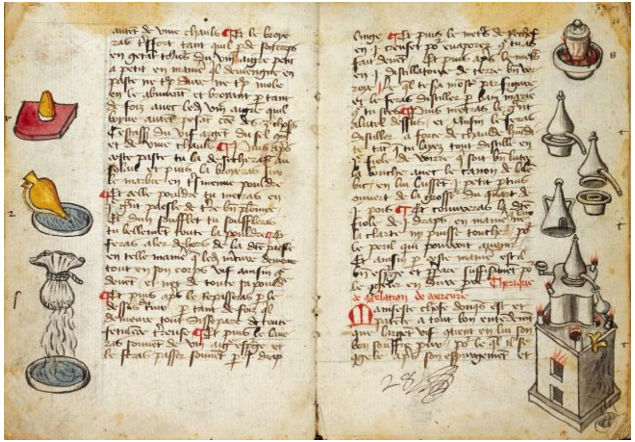
A Systems Community Initiative

FuSE Mini-Event: Introduction and Update, 29 March 2023

Olivier de Weck
Stream Lead “SE Foundations”

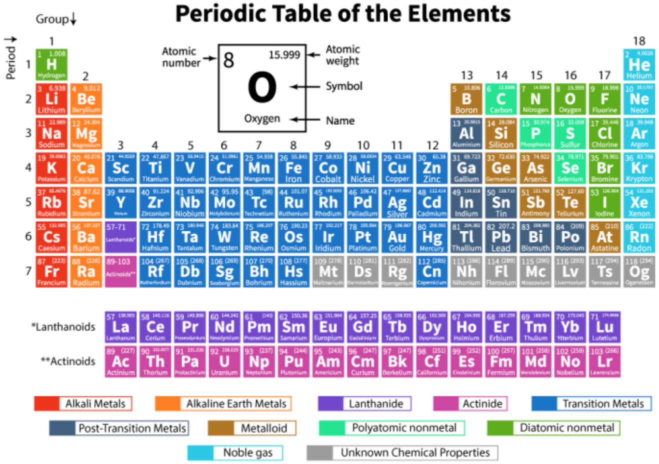
Joshua Sutherland
Deputy Stream Lead “SE Foundations”

From Alchemy to Chemistry



Book on Alchemy (recipes) – 1600s

Islamic and European alchemists developed a basic set of laboratory techniques, theories, and terms, some of which are still in use today. However, they did not understand the underlying building blocks of matter, still relying on the 4 elements of Greek philosophy.



Periodic Table of Elements – 1800s

In 1817, German physicist Johann Wolfgang Döbereiner began to formulate one of the earliest attempts to classify the elements. In **1829**, he found that he could form some of the elements into groups of three, with the members of each group having related properties. It took 100+ years to fill the table

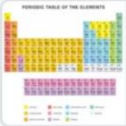
Alchemy – Chemistry – Chemical Engineering → **300+ Years**

Audience Survey

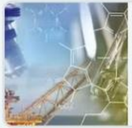
FuSE
Future of Systems Engineering

From Alchemy to Chemical Engineering: How mature is Systems Engineering today?

- Year 1623
- Year 1723



- Year 1823
- Year 1923

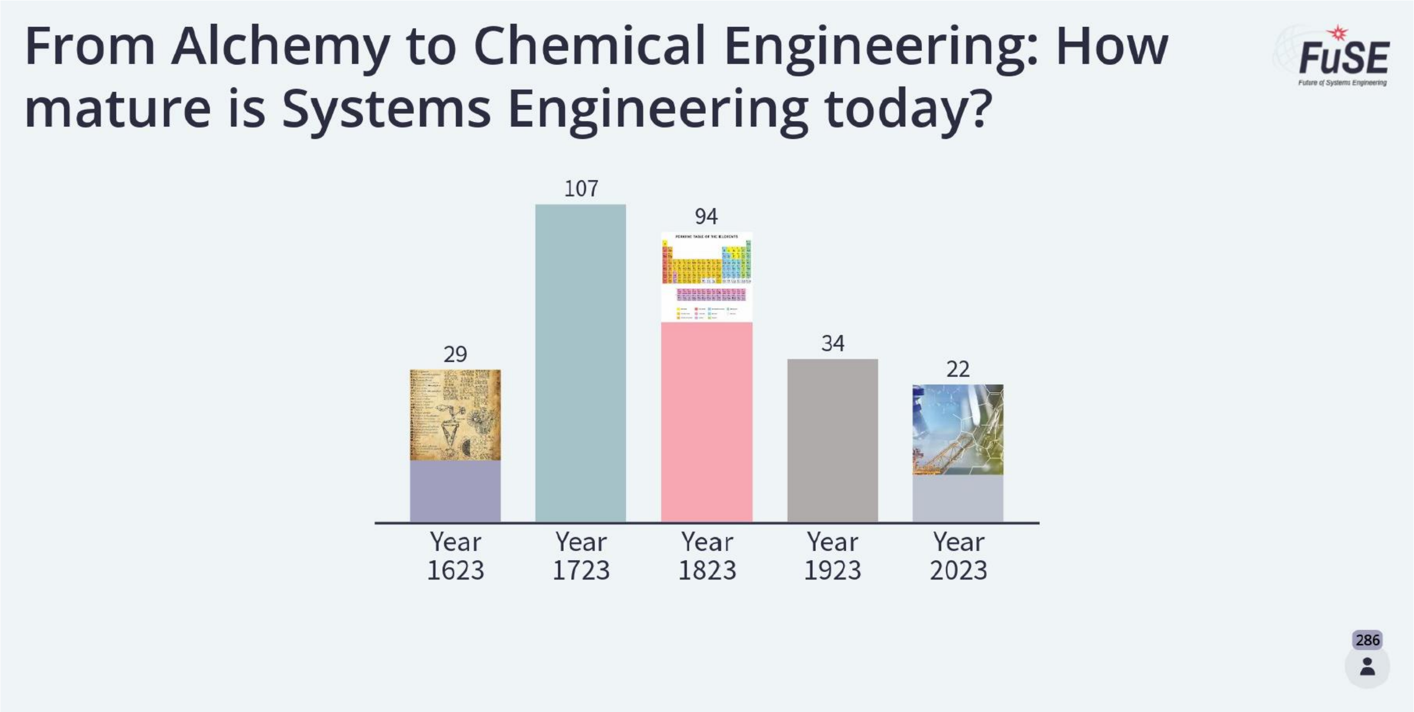


- Year 2023

Submit

Or use QR code

IW 2023 Audience survey result:
“Where are we on our SE journey?”



Where are we on our Systems Engineering (SE) journey?

- We are in a transition phase between practice (with plenty of heuristics and data) and the beginnings of a deeper theory
- What are the laws that can accurately predict the behavior of complex systems under a set of given assumptions ?
- In order for any "laws" to be accepted as true, there needs to be a set of experiments and data to validate (or falsify) them

Systems Engineering in 2023 is where Chemical Engineering was in 1823 !

Theoretical Foundations

"TO" state:

"The systems engineering foundations have a stronger **scientific and mathematical grounding** based on **advanced practices, heuristics, systems observable phenomena, and formal ontologies.** The foundations are shared across application domains, and provide additional rationale for selecting and adapting practices to **maximize value** for the particular application."

https://violin-strawberry-9kms.squarespace.com/theoretical-foundations

How are we approaching SE Foundations?

- **1. Quantification:**
  - Unless we can quantify what we speak about we are not really masters of the fundamentals
  - The deeper theoretical understanding of what drives performance, complexity, effort, cost, safety in systems requires this.
- **2. Experimentation:**
  - Claims will be subjected to the rigors of careful and repeatable experimentation (at different organizations, individuals at different locations) to either support or refute them.
  - Remain skeptical of any claims related to SE Fundamentals unless there is experimental evidence (either from natural or controlled experiments) to validate these ideas.
- **3. Work with other FuSE streams to make our findings operationalizable to doing great Systems Engineering**
  - What we discover will be made useful for doing work

Initial area of investigation

The First Law of Systems Science and SE: Conservation of Complexity

- First Law of Thermodynamics:
  - Conservation of Energy
  - The change in internal energy ΔU is equal to the heat *Q* added to the system minus the work *W* done by the system.

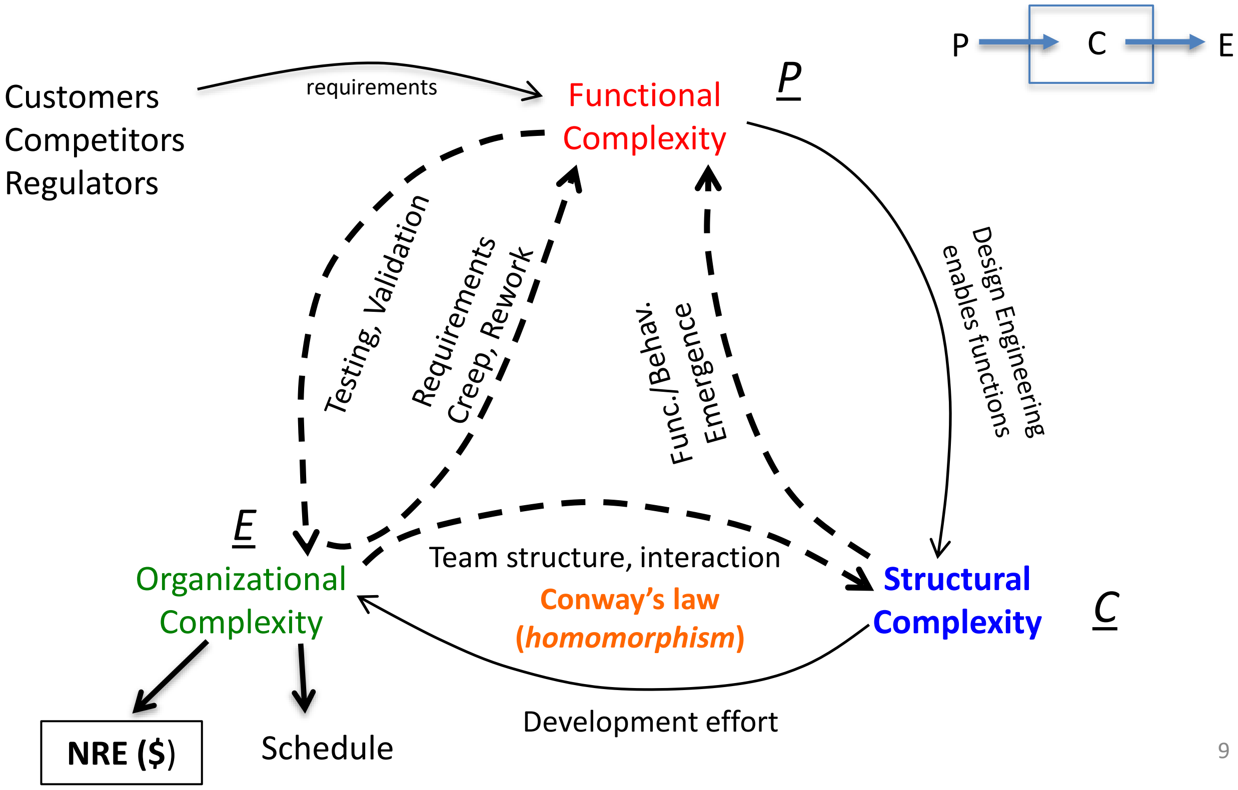
$$\Delta U = Q - W.$$

- The First Law of Systems Science and Engineering:
  - **Conservation of Complexity**
  - The change in complexity ΔC of the system is equal to a proportional change in expected performance ΔP minus the change in effort ΔE expended by the enterprise

$$\Delta C = \mu \Delta P - \varepsilon \Delta E$$

$$\varepsilon = -\frac{C^{1-m}}{2am} \qquad \mu = \frac{(1+kC^n)^2}{2Pmaxkn C^{n-1}(1-kC^n)}$$

Three Dimensions of Complexity



NRE Cost – Non-Recurrent Engineering Cost

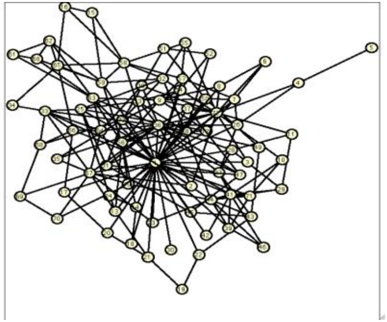
The Structural Complexity Metric

Structural Complexity, $C = C_1 + C_2 . C_3$

Complexity due to system topology (a scaling factor) typically > 1

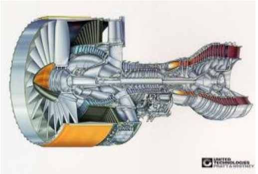
Complexity due to components alone (number and heterogeneity of components)

Complexity due to pair-wise component interactions (number and heterogeneity of interactions)

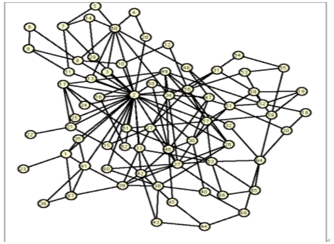


Sinha, Kaushik, and Olivier L. de Weck. "Empirical validation of structural complexity metric and complexity management for engineering systems." *Systems Engineering* 19, no. 3 (2016): 193-206.

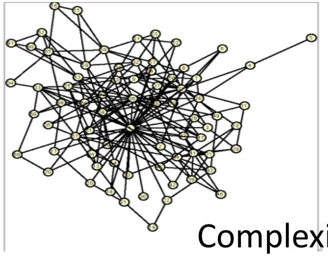
Empirical Data: Complexity Increase of Engines



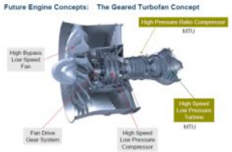
Old



Complexity = 351



Complexity = 499



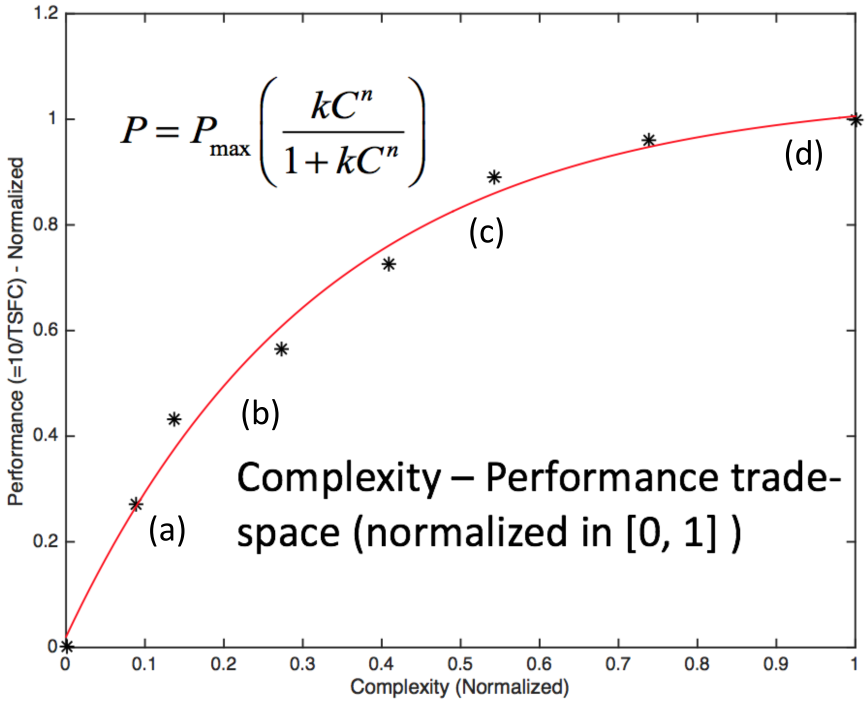
New

Complexity increase +42%

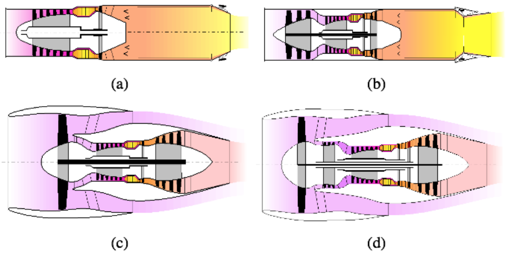
	C_1		C_2		C_3		C		C/C_{ML}		C_{new}/C_{old}
	Old	**New**	**Old**	**New**	**Old**	**New**	**Old**	**New**	**Old**	**New**	
Most Likely	161	188	126	184	1.51	1.69	351	499	1	1	1.42
Mean	179	244	141	240.4	1.51	1.69	392	650.3	1.12	1.30	1.65
Median	178	242	139	238.9	1.51	1.69	388	646.8	1.10	1.29	1.66
70 percentile	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*. Similar trend was observed in Printing Systems.

Diminishing Returns with Complexity

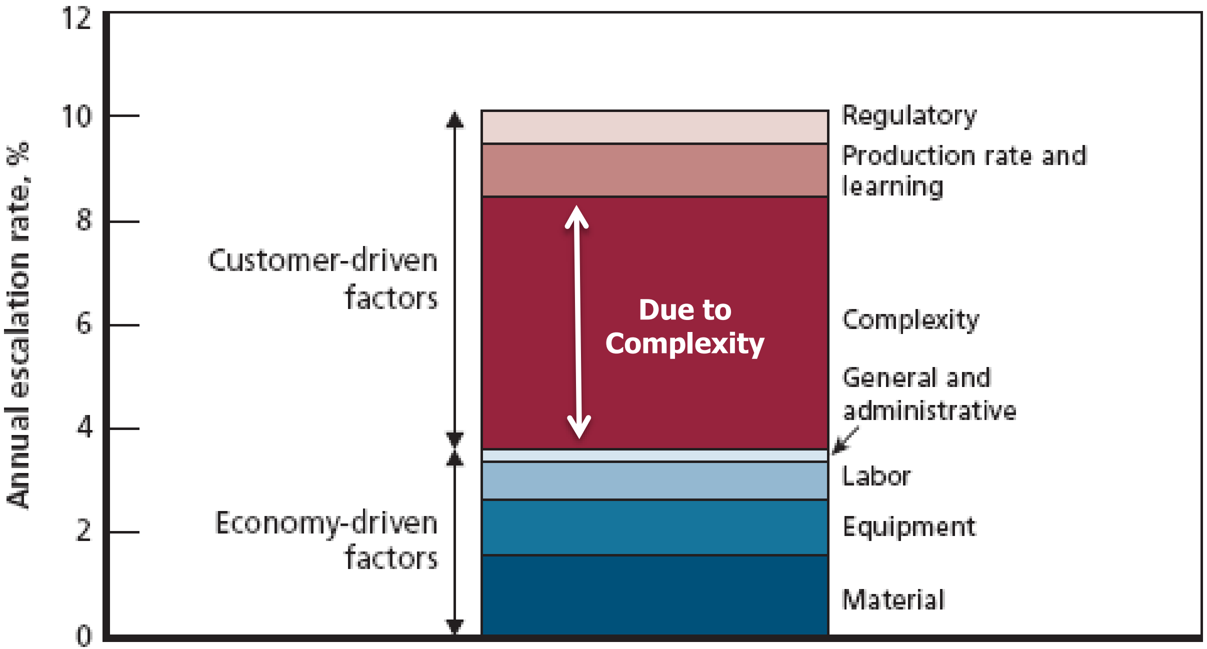


Left: Diminishing returns of normalized TSFC performance for air-breathing aircraft engines versus complexity, Bottom: evolution from turbojet to geared high BPR turbofans



What is driving this escalation of cost?

Contributors to Price Escalation from the F-15A (1975) to the F-22A (2005)

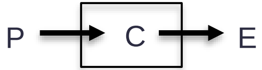


Source: DARPA TTO (2008)

First Law of Systems Science and Engineering (proposed)

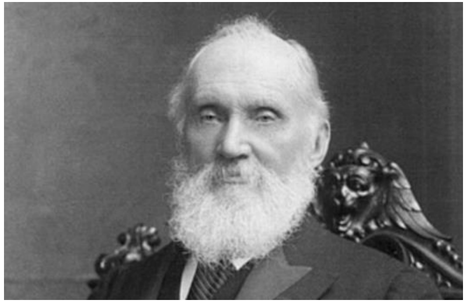
Conservation of Complexity

The change in complexity C of the system is equal to a proportional change in expected performance P minus the change in effort E expended by the enterprise



$$\Delta C = \mu \Delta P - \varepsilon \Delta E$$

Is this "law" true?



"When you can measure what you are speaking about, and express it in numbers, you know something about it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarely, in your thoughts advanced to the stage of science."

William Thomson, Lord Kelvin (1824–1907)

INCOSE FuSE

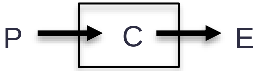
Los Angeles "Freewaytopia"

Source: https://www.engadget.com/hitting-the-books-freewaytopia-paul-haddad-santa-monica-press-153036975.html

Test the (proposed) 1st Law of Systems Science & Engineering

Conservation of Complexity:

The change in complexity C of the system is equal to a proportional change in expected performance P minus the change in effort E expended by the enterprise

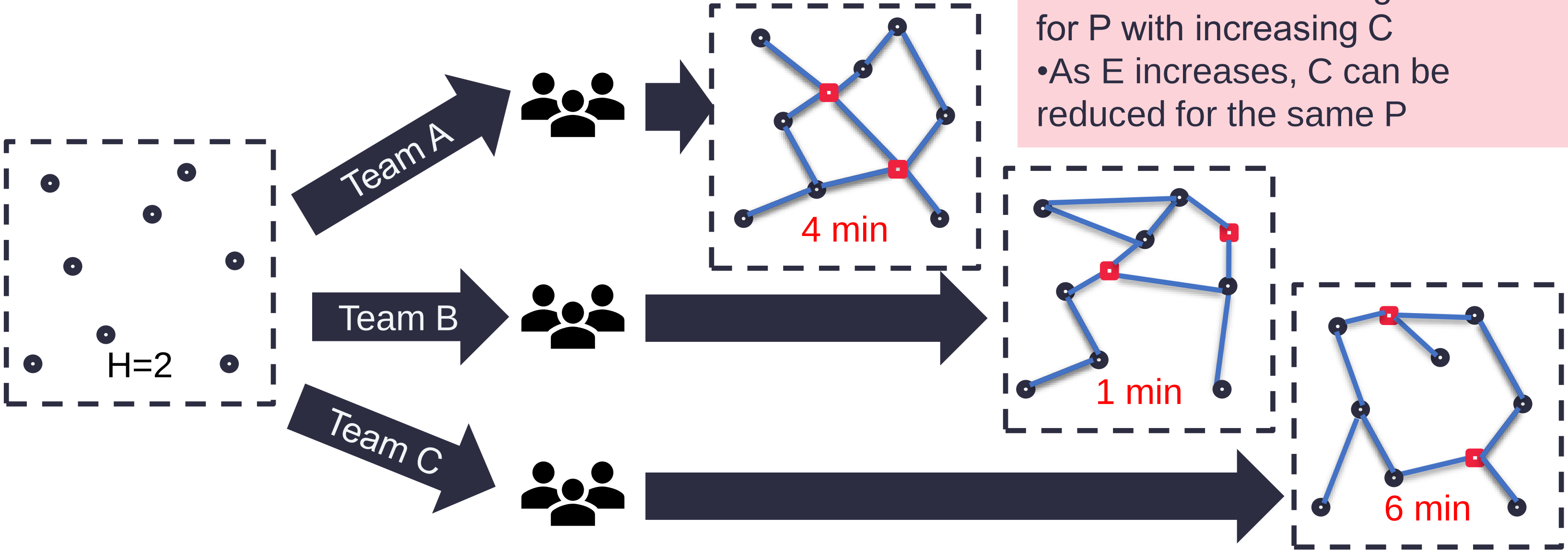


$$\Delta C = \mu \Delta P - \varepsilon \Delta E$$

Hypotheses tested:

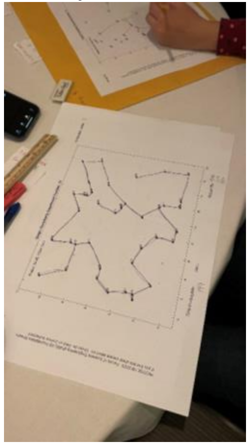
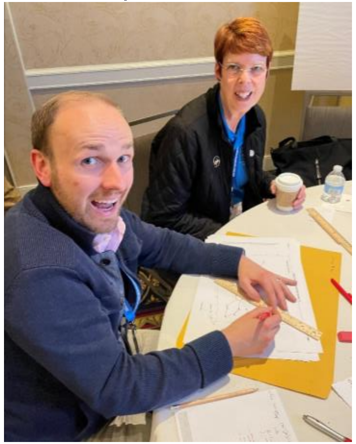
- Effort E (time) increases super-linearly with Complexity (C)
- The more effort a team spends the better the solution will be (P)
- There are diminishing returns for P with increasing C
- As E increases, C can be reduced for the same P

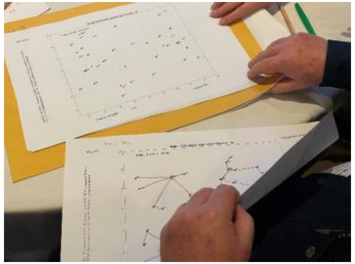
Designing a new transport system for a city.



Impressions on “Complexity Experiment”

60 participants. Session A: 40 Participants. Session B: 20 Participants.

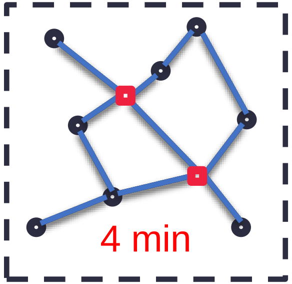





Details from “Complexity” Experiment

- **Observations** from the experiment:
  - Teams used **different approaches** which used more/less Effort E (time)
  - Teams produced **different designs** for each node network using more/less Effort
  - Teams developed **different heuristics** on their initial designs that they used in later sheets

- **Post Processing** currently being done at MIT:



1								1	
	1					1			1
		1							1
			1			1		1	
				1			1		
					1		1	1	
	1		1			1			
				1	1		1		1
1			1		1			1	1
	1	1					1	1	1

Performance P

- minimum average path length

Complexity C

- normalized graph energy of network

Effort

- Time spent designing the system

How are we approaching SE Foundations?

- **1. Quantification:**
  - Unless we can quantify what we speak about we are not really masters of the fundamentals
  - The deeper theoretical understanding of what drives performance, complexity, effort, cost, safety in systems requires this.
- **2. Experimentation:**
  - Claims will be subjected to the rigors of careful and repeatable experimentation (at different organizations, individuals at different locations) to either support or refute them.
  - Remain skeptical of any claims related to SE Fundamentals unless there is experimental evidence (either from natural or controlled experiments) to validate these ideas.
- **3. Work with other FuSE streams to make our findings operationalizable to doing great Systems Engineering**
  - What we discover will be made useful for doing work

Experiment to be re-run at EMEA WSEC 2023

- If you did not get chance to participate at IW 2023 please join in Sevilla Spain (due to nature of experiment, you need to be in the room to participate)

Systems Engineering Foundations Stream

INCOSE®

FuSE
Future of Systems Engineering

fuse@incose.net