





The First Law of Systems Science: Conservation of Complexity

INCOSE International Workshop 2023

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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





Audience Survey



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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 !

Fundamental Laws in Science

- First Law of Thermodynamics
 - Conservation of Energy
 - Rudolf Clausius 1850
- Second Law of Classical Mechanics
 - Conservation of Angular Momentum
 - Leonhard Euler 1736

What is the conserved quantity in Systems Science (and therefore Systems Engineering)?







Structural DSM of Wright Flyer







Connections 62 Physical 4 Mass Flow 11 Energy Flow 9 Info Flow Total: 86

NZF = 86/1,224= 7% density

<k>=~5

Design Structure Matrix (DSM) – captures structure of elements of form



Year of Entry into Service

Norm Augustine, Augustine's Laws, 6th Edition, AIAA Press, 1997.

Functional Requirements Explosion in Aviation





Image by MIT OpenCourseWare.







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)

Three Dimensions of Complexity





NRE Cost – Non-Recurrent Engineering Cost

The Structural Complexity Metric



Structural Complexity, $C = C_1 + C_2 \cdot C_3$

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

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



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.



Experiment: We slow down w/complexity





Trend towards more distributed architecture with higher structural complexity and significantly higher development cost^{*}. Similar trend was observed in <u>Printing Systems</u>.



Diminishing Returns with Complexity





SYSTEMS ENGINEERING VISION 2035

ENGINEERING SOLUTIONS FOR A BETTER WORLD

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."

Complexity and Value Maximization



Complexity budget C* is the level of complexity that maximizes system Value !



$$P = P_{\max}\left(\frac{kC^n}{1+kC^n}\right)$$

1

$$V = \frac{P}{NRE} = P_{\max}\left(\frac{k}{a}\right) \left[\frac{C^{(n-m)}}{1+kC^n}\right] = S\left[\frac{C^{(n-m)}}{1+kC^n}\right]$$

Value V is the ratio of Performance P over non-recurring Effort E → what is V*?

$$C_*^n = \frac{\left(\frac{n}{m}\right) - 1}{k}; P_* = P_{\max}\left(1 - \frac{m}{n}\right)$$
$$NRE_* = a \left[\frac{\left(\frac{n}{m}\right) - 1}{k}\right]^{\frac{m}{n}}; V_* = S\left(\frac{m}{n}\right) \left[\frac{\left(\frac{n}{m}\right) - 1}{k}\right]^{\left(1 - \frac{m}{n}\right)}$$

Example: Complexity Target to optimize Value





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



- First Law of Thermodynamics:
 - Conservation of Energy

- $\Delta U = Q W.$
- The change in internal energy ΔU is equal to the heat Qadded to the system minus the work W done by the system.
- The First Law of Systems Science and Engineering:
 - Conservation of Complexity $\Delta C = \mu \Delta P \varepsilon \Delta E$
 - 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

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

Validation of the 1st Law: Successful vs Failed Systems



- CoBRA (Aerospace Corp., 2008) Complexity Index based on analysis of historical data.
- Projects that were highly complex but tried to cut development cost had high failure rates



Key Messages



- Complexity C of artificial (and natural?) systems has been increasing
- This is driven by customers, competition, and regulation → functional performance P → structural complexity C → organizational effort E
- A rigorous measure of complexity is based on graph energy of DSM
 - C = C1 + C2*C3;
 - C3: Graph Energy is a measure of topological complexity
 - Explicit complexity-based budgeting with clear targets is needed in SE
- First Law of Systems Science and Engineering (according to de Weck-Sinha):
 - Conservation of Complexity
 - Given a set of functional requirements P, establish minimum needed structural complexity C, and calculate organizational effort E (NRE) to satisfy the first law
- Violating the first law can lead to project or system failure !



INCOSE IW 2023 Future of Systems Engineering (FuSE)

Foundations Stream