International Council on Systems Engineering
A better world through a systems approach

System Adaptability and Adaptive/Adaptable Systems Engineering (ASE)

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INCOSE System Adaptability WG

*Dr.Zhu is a Technical Director in BAE Systems, though this talk does not represent BAE Systems..

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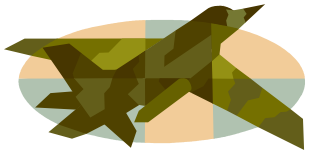


Motivations

- ***Pain*** in complex system development
  - Significant cost overrun
  - Significant schedule delays

especially, Aerospace and Defense industry (A&D).
Early stage architecture design defects are major causes.

- Architecture design must be
  - Not rigid
  - Not overly designed which are:
    - Costly, sometimes unrealistic, e.g. aerospace
- Thus: for design sustainability, must be adaptable to changes.
- But what is an adaptable system in Systems Engineering?

Adaptability

- **Dictionary Definition:**

adapt means "to make fit (as for a new use) often by modification"

(Merriam-Webster, Inc.)

- **History:**
  - Traditionally used in ecosystems
  - Started in engineering, since 1948 Nobert Weiner, invented Control Theory. Many communities: adaptive control, IT, mechanical, etc.

- **Systems Engineering:**

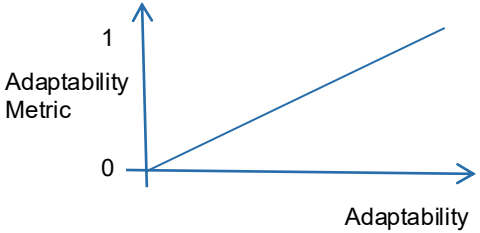
System Adaptability:

A system's ability to satisfy mission and requirement changes, with or without modifications.

(Ref: SEBoK Definition)

Measure: Adaptability Metric:

- E.g. utility function value in [0,1]



Three Fundamental Factors:

- **Missions & Requirements Evaluation Space (MRES)**
  - Capture both current and future potential needs
- **Design Space**
  - A set of design alternatives and/or states
- **Switching Costs**
  - Costs incurred from switching from one system state to another (for real-time adaptation)
  - Costs incurred from switching from one system design to another (leverage reuse)

Note: more generic term than reuse cost

- Missing any of these, result in "Inverted Measure" flaw:
  - More adaptable system may be ranked lower than a system with lower adaptability.

Two Types of Adaptations:

- Real-Time
  - E.g. robot responds environment
- Non-Real-Time
  - E.g. product design: design a product from a previous one

Adaptable Architecture: Example – Aircraft Engines

1. Missions & Requirements Evaluation Space (MRES):

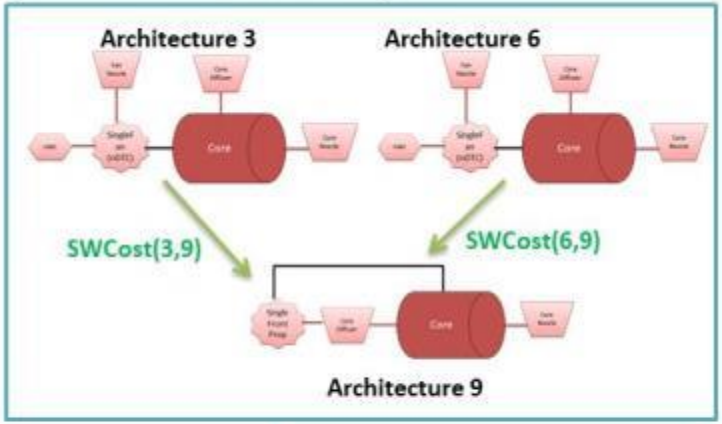
Current Needs:

2	3
low	low
low	low
mid	short
required	required

Potential Needs:

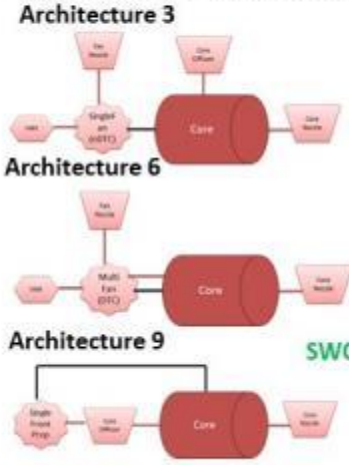
	1	4	5	6
Takeoff gradient	low	High	high	high
Climb rate	low	Low	low	low
Cruise range	long	Long	mid	short
Preference	optional	optional	optional	optional

Trade Study:

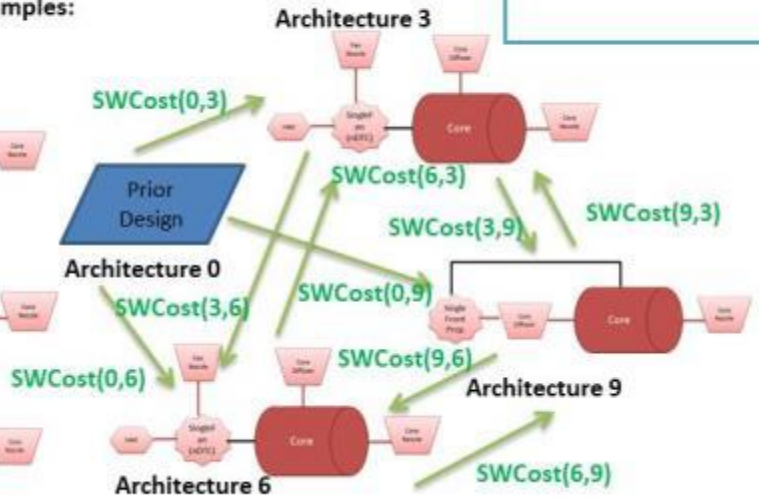


2.Design Space:

(Architecture 1 – 12). Examples:



3.Switching Costs:



Suppose:
Architecture 3,6: only meet current needs.
Architecture 9: meets both current & potential needs
SWCost(0,3) ≈SWCost(0,6) << SWCost(0,9)

Decision:
If SWCost(3, 9)<<SWCost(6,9), Pick Architecture 3.

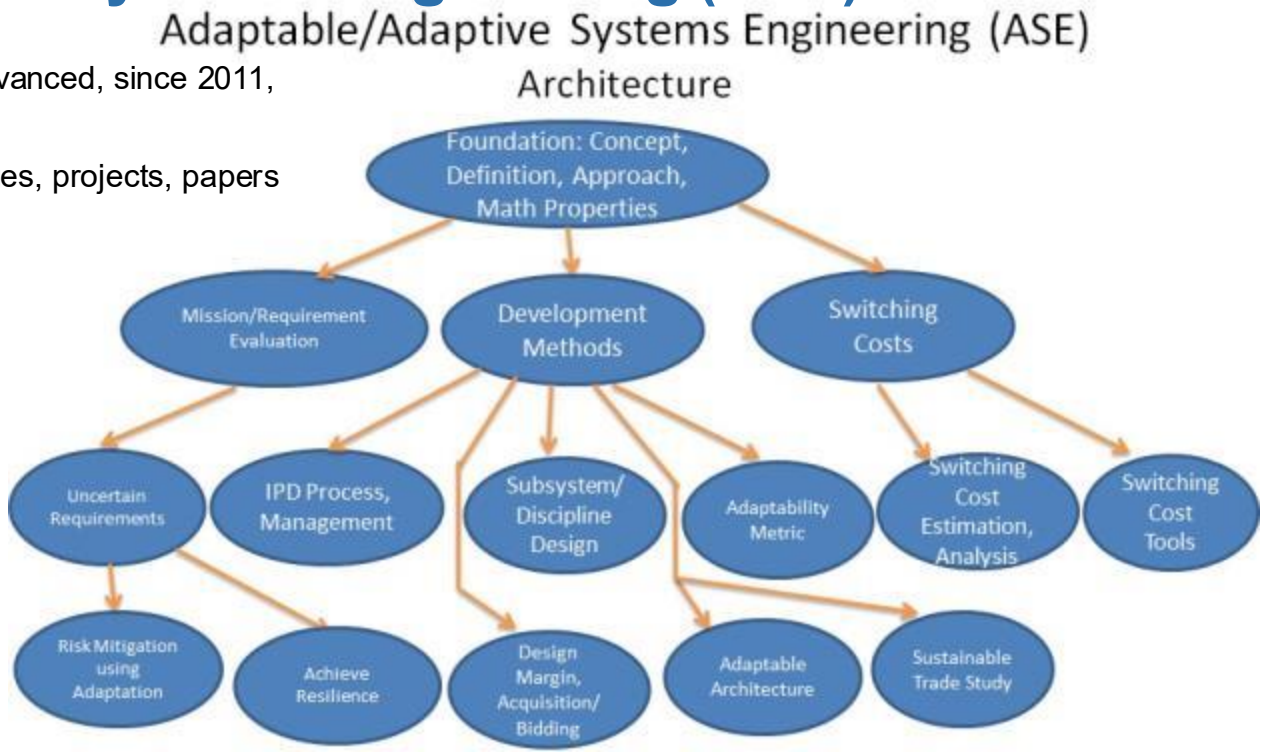
Insight: If potential needs not realized, stay with Architecture 3. Otherwise, switching to Architecture 9 costs least. Optimal !

Adaptive/Adaptable Systems Engineering (ASE)

- Lots of knowledge developed and advanced, since 2011, in INCOSE and IEEE
- Each bubble represents results, usages, projects, papers

Example Techniques:

- Sustainable Trade Study
- Switching Costs
- Uncertain Requirements and Missions
- Design Process and Organizational Adaptation
- Supply Chain and Acquisition
- Relationship with other SE Disciplines
- Complex Adaptive Systems



Wide Usages

- Boeing standard design practice guidelines
- Raytheon Mission Systems
- California Precipitation Systems
- Green Communication Systems
- Boeing Tool Selection
- UAS Traffic Management
- SW Cost Tools
- Adaptive City Planning
- Adaptive Entrepreneurship
- Risk Management
- Supply Chain, Acquisition with Adaptability Metric
- Resilience vs. Adaptability
- Climate Change Mitigation Study
- ….

Courtesy SEBoK news

INCOSE SE Vision 2035:

More than 20 hits on "adapt":

tolerant, secure, robust, resilient, and adaptable will be a fundamental part of systems engineering practices. Visualization tools will enable interactive

system representation. Evolving needs, external context, and anticipated failure scenarios are central to the architecture process resulting in flexible, resilient, and adaptable architectures.

Backup

Measure

Adaptability Metric

- Once 3 fundamental factors were captured, based on Adaptability definition (SEBoK), one can define adaptability metric **will be consistent !**
- Example metric: Value [0, 1], higher represents better adaptability

Adaptability Category	Value Range	Meaning
Perfectly Adaptable	1	The system supports all the required and optional missions with zero additional costs. This is the most adaptable situation one system can achieve.
Mostly Adaptable	[0.5, 1)	The system supports all the required and optional missions with an acceptable amount of cost for additional engineering. The acceptable cost C_t can be a user-specified threshold based on switching cost function.
Partially Adaptable	(0, 0.5)	The system supports all the required and some (but not all) optional missions within the acceptable amount of cost C_t.
Non-Adaptable	0	The system supports only the required missions and supporting optional missions becomes infeasible within the acceptable cost constraint (> C_t).

REF: Zhu, H., Murray, B., de Weck, O., Skelding, R., Shougarian, N., Zeidner, L., & Arnold, E. Adaptability Metric Analysis for Multi-Mission Design of Manufactured Products and Systems. In INCOSE International Symposium (2016, July).

Usefulness: we back you up!

Once 3 fundamental factors captured, use adaptability metric, you can:

- Know how adaptive your system is
- More importantly: elevated the work's theoretical level:

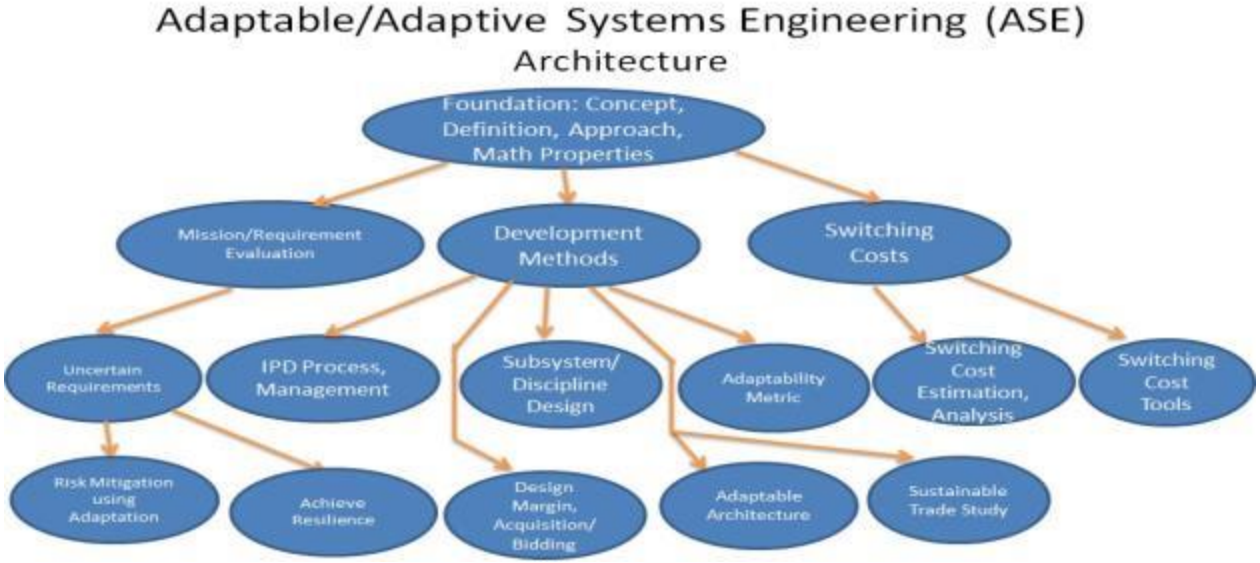
→Your rigorously and confidently claim your system is adaptive, has high adaptability **is strongly supported and justified THEORECTICALLY, generalized and compatible with:**

other domains (control, SW, eco, etc.) AND

Adaptive Systems Engineering (ASE)

Adaptable Systems Engineering (ASE)

- Introduced by Zhu, et.al. in 2011.
- Since 2011, driven by Zhu, Arnold, with colleagues from INCOSE and IEEE SE communities.
- Many R&D results and industrial adoptions.



Next, we will review some existing results and use cases (some "bubbles" above)

Sustainable Trade Study

ASE Domain 1

More on Sustainable Trade Study

- Ref: William M Brooks, V. Chandrasekar and Rob Cifelli, “Digital Twin Support in Adaptability of the Advanced Quantitative Precipitation Information System”, Complex Adaptive Systems (CAS) conference 2025

Switching Costs

ASE Domain 2

Gaps and Results

- Around 2010:
  - We were the first proposed *development switching cost* estimation method for:
    - Generic system
    - Any product size

      NOTE: Another approach: Parametric (COSYSMO 2 and above): restricted to large data/project size

REF: Zhu, Haifeng. "Developing Case-Based Costs Estimation: A Recursive Approach and Case Study." INCOSE International Symposium. Vol. 28. No. 1. 2018.

More Results:

- Model-Based Switching Costs
  - Zhu, H., Hemenway, J. M., Wang, G., & Agarwal, N. K. (2024, July). Model-Based Switching Costs. In INCOSE International Symposium (Vol. 34, No. 1, pp. 1964-1979).
- Lifecycle Switching Costs
  - Y. H., Lifecycle Switching Costs, INCOSE International Symposium, 2025
  - Y. H., Adaptation with Lifecycle Switching Costs for Complex Adaptive System Development, Complex Adaptive Systems (CAS) Conference, at MIT, 2025
- Switching Cost Tools
  - Commercial: SEER, etc.
  - Free:
    - COSYSMO v2 or v3: restricted to large size
    - SWCost Tool v1: any size

Uncertain Missions and Requirements

ASE Domain 3

Engineering with Uncertain Requirements

- Modeling uncertain requirements in MRES

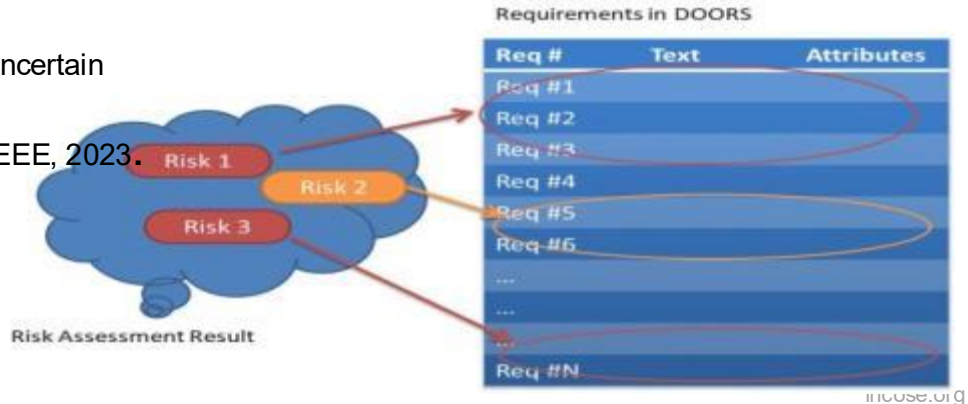
  Earlier Example: Pratt & Whitney aircraft engine design

  Ref: Zhu, de Weck, Arnold, et al. "Adaptability Metric Analysis for Multi-Mission Design of Manufactured Products and Systems." INCOSE International Symposium. 2016.

- Uncertain requirements discovery

Ref: Zhu, H. "A Development Procedure for Discovering Uncertain Requirements."

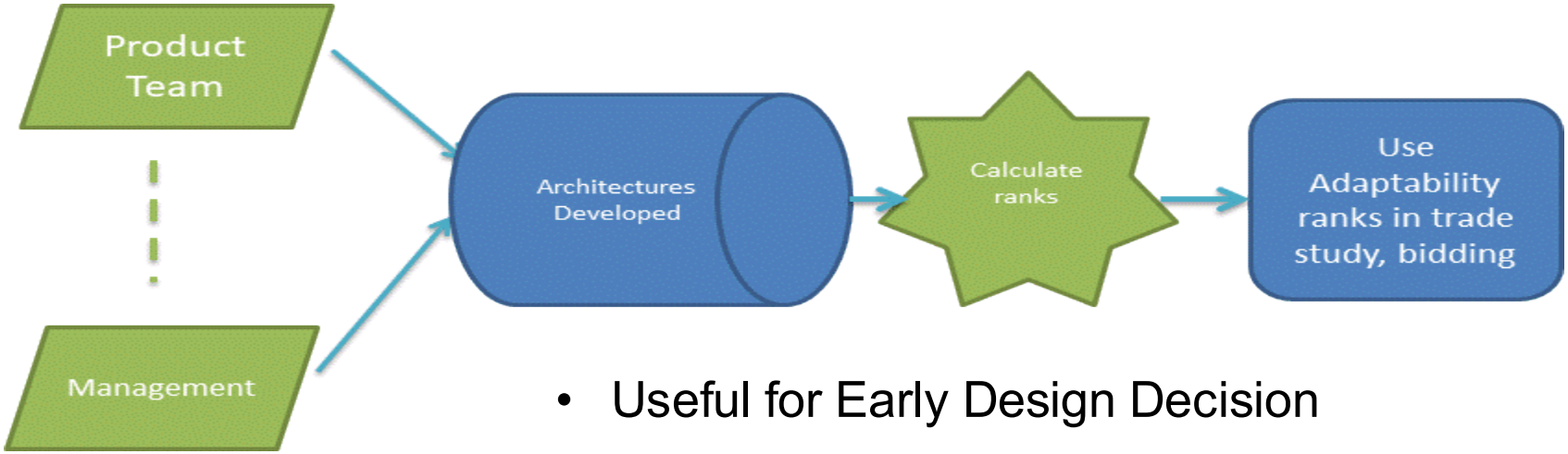
2023 IEEE International Systems Conference (SysCon). IEEE, 2023.



Design Process and Organizational Adaptation

ASE Domain 4

Process



- Useful for Early Design Decision

Zhu, H. "Designing systems with adaptability in mind." *Complex Systems Design & Management: Proceedings of the Sixth International Conference on Complex Systems Design & Management, CSD&M 2015*. Cham: Springer International Publishing, 2015.

Adapting Non-MBSE to MBSE

- Organizational Issues:
  - Lack of expertise
  - Conflict with MB Certification
- Proposed Organizational Change
  - 3-factors
    - Top Leadership
    - Chief-Architect and Architect Group
    - Multidiscipline team

Ref: Zhu, Haifeng, and Grant Wang. "Tackling Model-Based Development Process and Organizational Challenges." *2024 IEEE Aerospace Conference*. IEEE, 2024.

Supply Chain and Acquisition

ASE Domain 5

Supply Chain: Acquisition

	A	B	C
Cost	xx	yy	zz
Adaptability ranks	0.25	0.7	1
Other information			
…			

Bidding Table

Ref: Zhu, H. "Controlling Costs and Margins of Engineered Systems." *INSIGHT* 22.1 (2019): 37-40.

Relationship with other SE Disciplines

ASE Domain 6

Crossing Disciplines

- With Risk Management WG
  - Insight: Multi-stage adaptation, rather than one-shot high risk decision.
  - Ref: Zhu, et. al., ”System Adaptability as a Method of Risk Mitigation”, CAS 2025.

- With PM-SE WG:
  - Insight: Adaptability metric for can be used to choose proposal bidders
  - Ref: Zhu, “Controlling Costs and Margins of Engineered Systems”, INCOSE INSIGHT, 22(1), 37-40, 2019.
  - a
- With Resilience WG
  - Insight: Resilience addresses adversarial situation, Adaptability addresses both adversarial and beneficial situations.
  - Ref: Zhu, Cureton, et. al. “Relationship between Adaptability and Resilience”, submitted to INCOSE International Symposium, 2025.

Crossing Disciplines – Cont'

- With Complex Systems WG
  - Insight: Complex Adaptive Systems.
  - Ref: "Shaping the Future with Complex and Adaptive Systems", Panel in IS 2025.

- Entrepreneurship
  - Insight: plan for uncertainties, minimize switching cost path
  - Ref: Barton, R, Zhu, H., "How Today's Entrepreneurs Can Use Adaptive Systems Engineering to Create Successful Businesses", under review IEEE ISSE, 2025.

- Adaptive City Planning, Smart Cities
  - Ref: Zhi, H., Tepjit, S. and Barton, R, "Adaptable City Planning", under review IEEE ISSE, 2025.

Complex Adaptive Systems

ASE Domain 7

Complex Adaptive System

- Complex Adaptive Systems (CAS)
  - Complex + Adaptive

Cross-Paths:

- Result 1:leverage complexity metric to describe switching cost

Ref: Zhu, H., Shougarian, N., Ojard, G., Sinha, K., de Weck, O. and Arnold, E., “Exploring Early Stage Cost-Estimation Methods Using Off-the-Shelf Tools: A Preliminary Study”, International Conference on Complex Systems Design & Management, (CSD&M), Paris, 2016.

- Result 2: ASE vs. Emergent Behaviors

Ref: Zhu, Y, “Adaptation of Lifecycle Switching Costs for Complex Adaptive System Development”, Complex Adaptive Systems (CAS) Conference 2025.

Ref: Lee, W-J., Zhu, H. and Aghdam, A., “Climate Change Mitigation as a Complex Adaptive System”, Complex Adaptive Systems (CAS) Conference, at MIT, 2025.

Result 3: ASE vs. Open System Boundaries

- ASE can tackle open system boundaries, through:
  - Adaptable Architecture
    - Ref: Zhu, H., Murray, B., de Weck, O., Skelding, R., Shougarian, N., Zeidner, L., & Arnold, E. “Adaptability Metric Analysis for Multi-Mission Design of Manufactured Products and Systems”. In INCOSE International Symposium, 2016.
  - System/Subsystem/Discipline Design
    - Ref: Zhu, H. "Applying Mission-Based Adaptability to Discipline Designs." INCOSE International Symposium, 2019.