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

System Adaptability and Adaptive/Adaptable Systems Engineering (ASE)

Haifeng Zhu*, Ph.D.
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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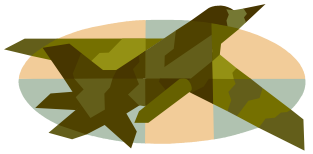


Motivations

- ***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:**

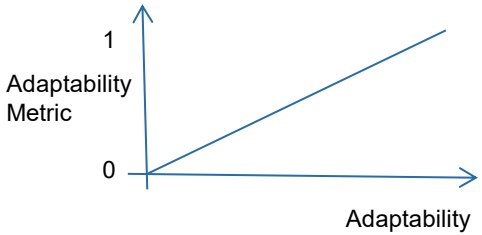
System Adaptability:

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):

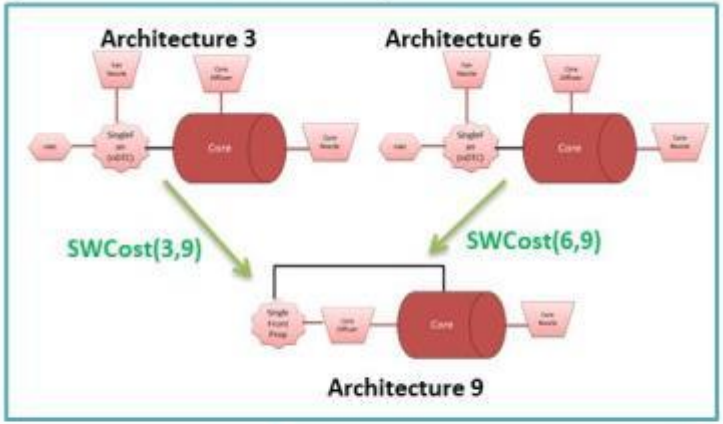
Current Needs:

2	3
low	low
low	low
mid	short
required	required

Potential Needs:

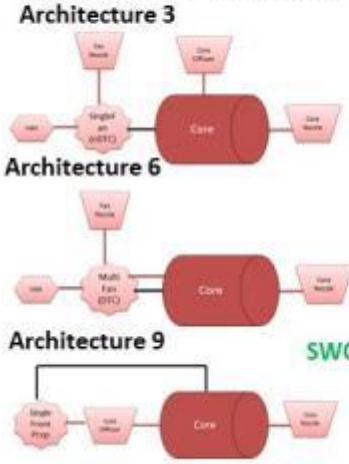
	1	4	5	6
Takeoff gradient	low	High	high	high
Climb rate	low	Low	low	low
Cruise range	long	Long	mid	short
Preference	optional	optional	optional	optional

Trade Study:

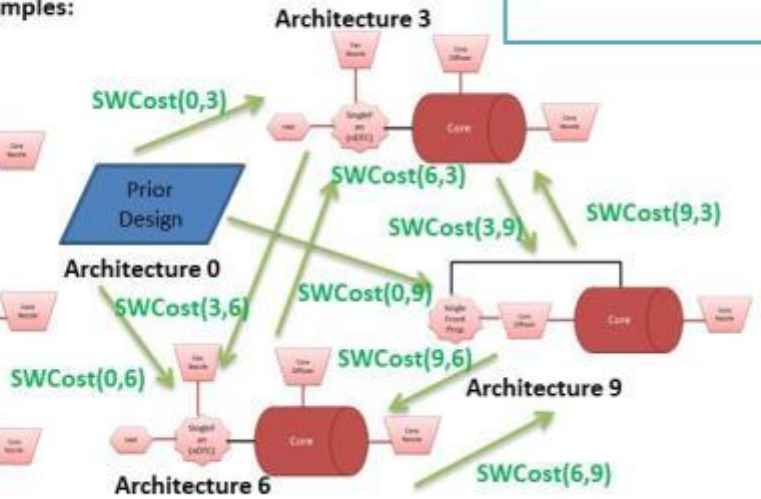


2.Design Space:

(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.

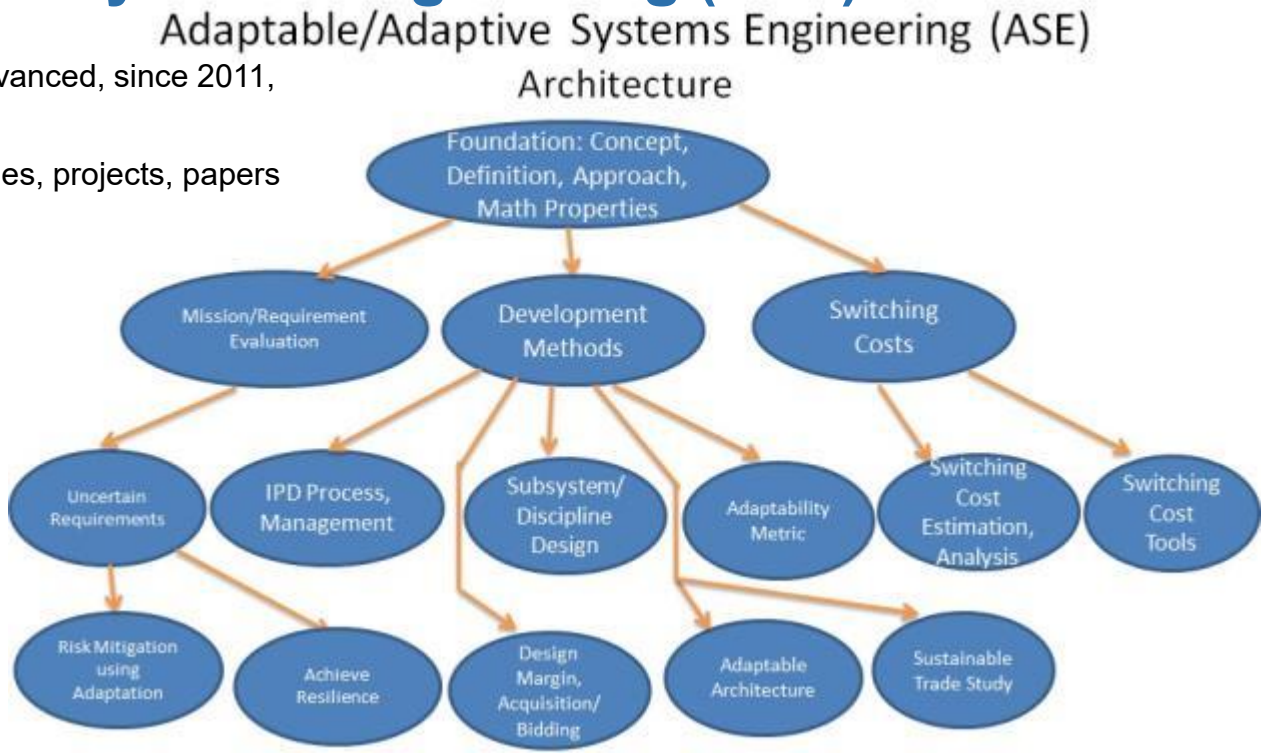
Insight: If potential needs not realized, stay with Architecture 3. Otherwise, switching to Architecture 9 costs least. Optimal !

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

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:

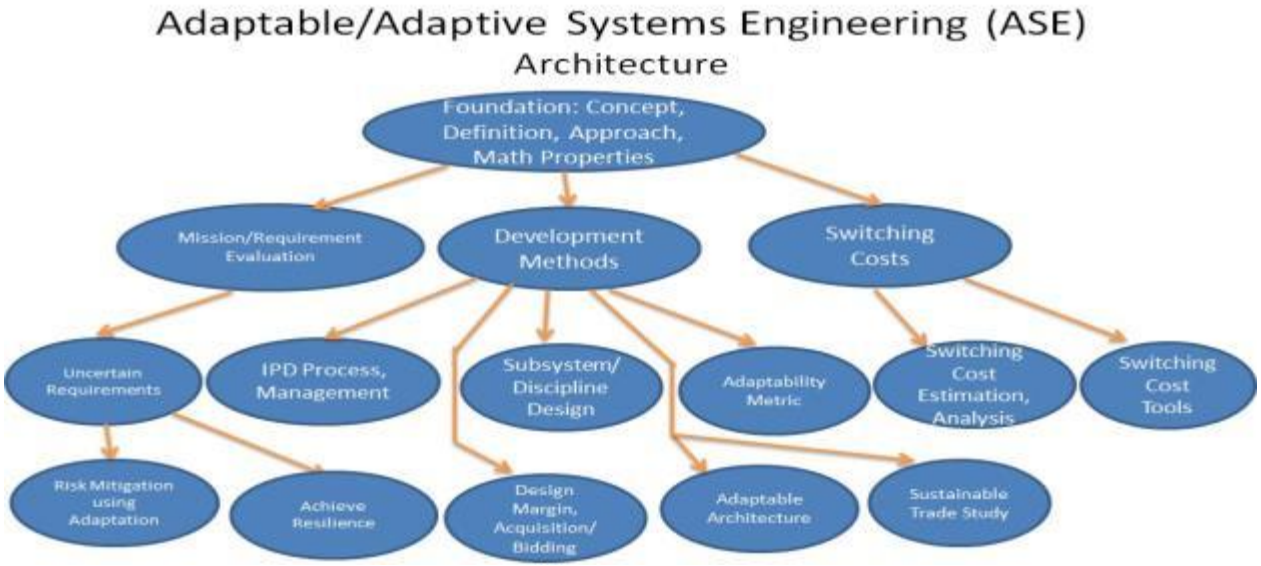
→Your rigorously and confidently claim your system is adaptive, has high adaptability **is strongly supported and justified THEORECTICALLY, generalized and compatible with:**

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

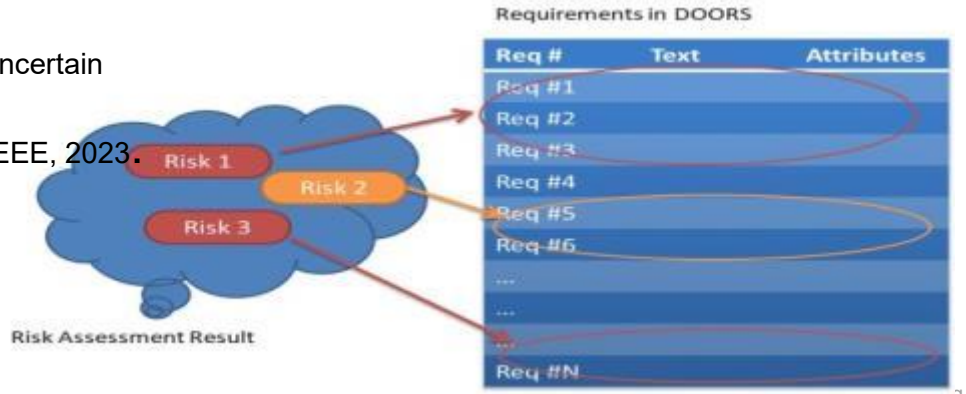
  Earlier Example: Pratt & Whitney aircraft engine design

  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."

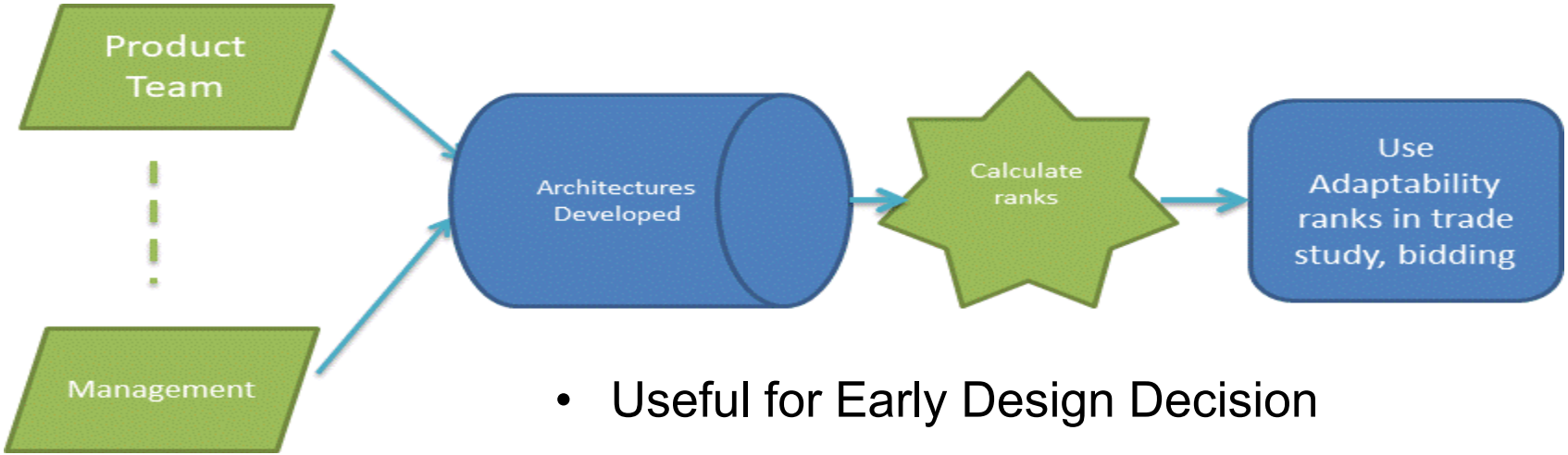
2023 IEEE International Systems Conference (SysCon). IEEE, 2023.



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.