26th annual INCOSE international symposium
Edinburgh, UK
July 18 - 21, 2016

Adaptability Metric Analysis for Multi-Mission Design of Manufactured Products and Systems

Haifeng Zhu[1], Brian Murray*, Oliver de Weck[2],
Randy Skelding[3], Narek Shougarian[2], Lawrence Zeidner[1], Eileen Arnold[4]
[1]United Technologies Research Center
[2]Massachusetts Institute of Technology
[3]Pratt and Whitney
[4]UTC Aerospace Systems

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*Participated while employed by United Technologies Corporation

This research was partially developed with funding from the Defense Advanced Research Projects Agency (DARPA) and the Air Force Research Laboratory (AFRL). The views, opinions, and/or findings contained in this presentation are those of the presenter(s) and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.

Outline

- Introduction
- Mission Evaluation Space
- Adaptability Metric
- Example Case
- Conclusion

Introduction

- Adaptability of system architectures is important
  - Flexibility without requiring significant up-front investment
  - Dynamics of customers needs/market, technologies, policies

Adaptability

- Original meaning of adaptability in ecosystem
  - Can be formulated as:

$$\lim_{\{t \to \infty\}} P_t(S \to S' | E) = \lim_{\{t \to \infty\}} P_t(S \to S')$$

Previous Studies

- (Ross, A., et. al. 2007)
  - Change agent is internal
  - Depends on how many configurations the current one can switch to
- (Gu, P., et. al. 2004)
  - Summation of normalized savings in change tasks
- (Shaw, et. al., 2001)
  - Objective measures are needed
- Some others
  - Rely on specific modeling methods that bring in restrictions of those methods

Analysis to Previous Studies -1

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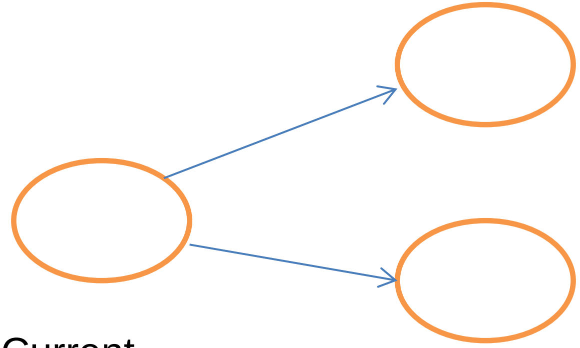
- Ross, A., et. al. 2007:
  - Focused on how many configurations can be switched to



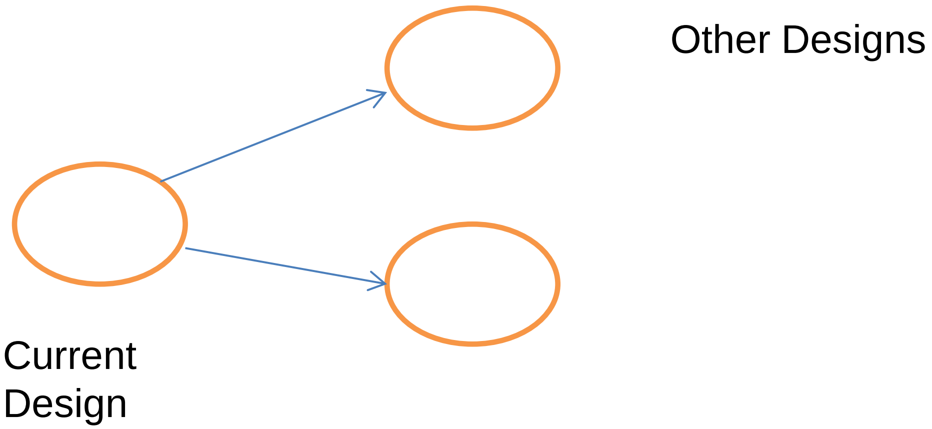
Other Configurations

Current Configuration

We need indications of:
Are these configurations maintaining the same goal of the system? Are they useful?

Analysis to Previous Studies -2

- (Gu, P., et. al. 2004): Summation of normalized savings in change tasks
  - Focused on how many designs can be switched to



We need indications of: Are these other designs useful? How many mandatory/optional goals (performance, functional) are satisfied?

Analysis to Previous Studies -3

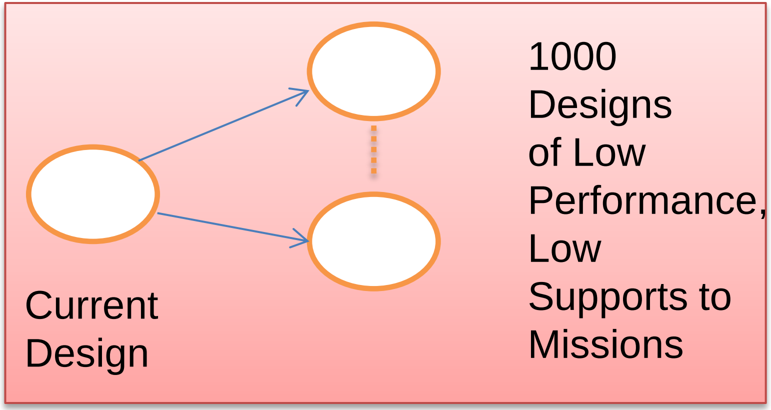
- (Shaw, et. al., 2001)
  - Objective measures are needed
    - Depends on user satisfaction
    - We need a metric that depends on system design characteristics

Evaluating Adaptable Systems

- If we follow the original meaning of adaptability in ecosystems
  - Encourage common criteria in research
  - Ensure the metric reflects truly adaptable system

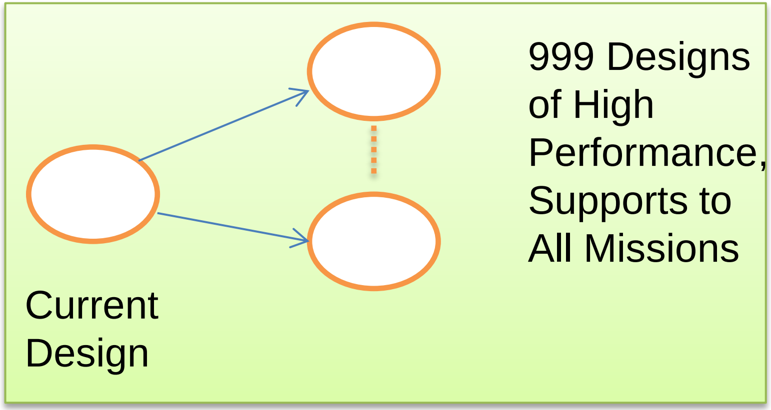
Otherwise, **counter-example** can happen:

High adaptability score



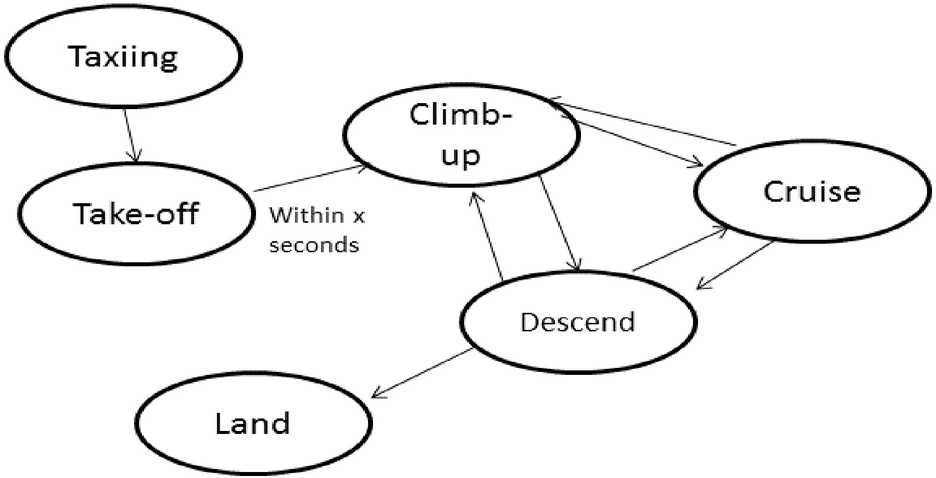
vs.

Low adaptability score



Mission Evaluation Space

- Characterize system goals
- Mission state machine
  - A mission: trajectory



- Support to a mission x:

$$S(x) = [0,1]$$

Example: Simplified missions of an airplane engine

Reference: Federal Aviation Administration FAR 33

How to Characterize Some Missions as More Important?

- Existing methods:
  - Weight
  - Probability

- Good enough?

How to Model Some Missions as More Important?

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- Not suitable:
  - Counter-example for “weights”: 10 unimportant missions with weight 0.1 = 1 important mission with 1?

$$\sum_{\{i=1\}}^{10} 0.1 = 1$$

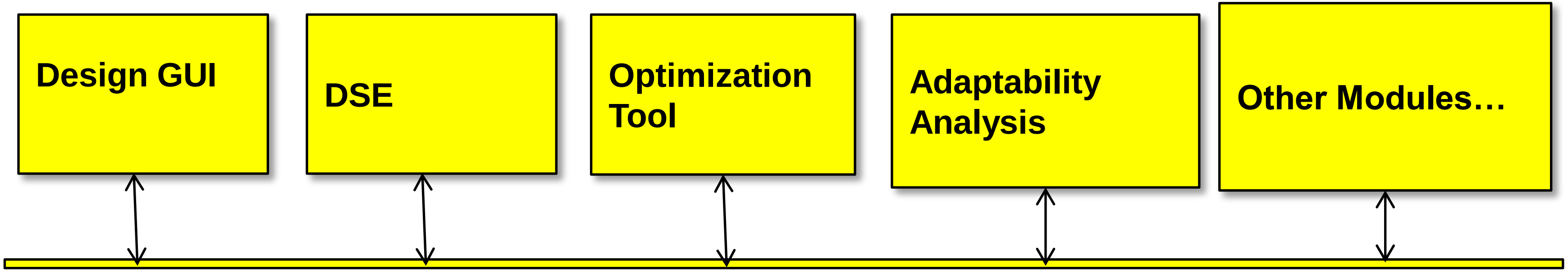
  - Counter-example for “probabilities”: missions with low probabilities may actually be important and must be supported

Our Concept

- Missions: two types
  - Required missions: R
  - Optional missions: Q

  E.g., S(Q) indicates how many optional missions are supported
- Each mission can then be associated with a list of user-defined properties:
  - E.g., Financial gain, probabilities and weights, etc.
- Use mission space in adaptability definition
  - Overcame problems with some existing work: missing elements of modeling goals/missions

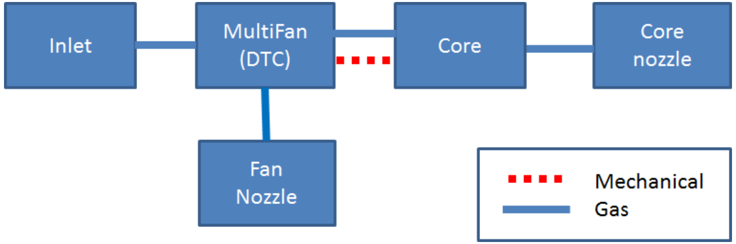
System Design Tool Chain Example

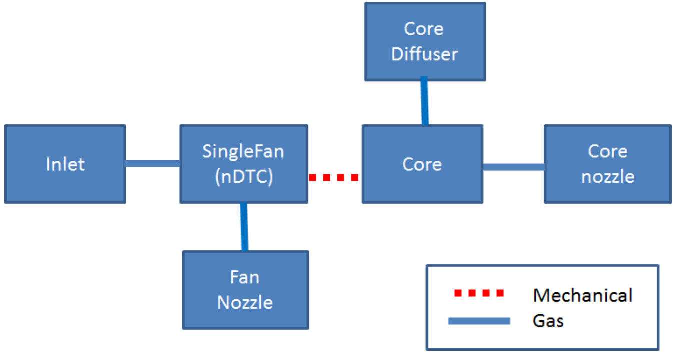


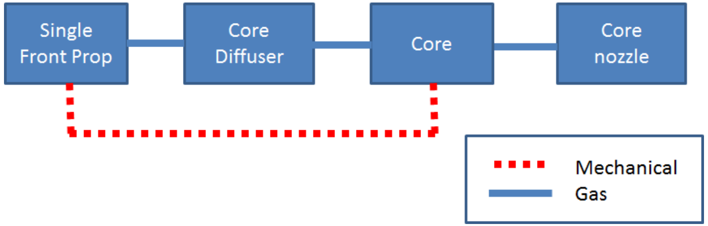
GUI: Graphical User Interface
DSE: Design Space Exploration: Generate ALL possible designs, based on all possible connection and parameterizations of all available components

Example Case: Aircraft Engine

- Engine architectures generated with DSE







Adaptability

- System goal: all the missions defined in evaluation space
- Definition:
  - The ability of a system in fulfilling the goals when facing changes
- Categories:
  - Perfectly Adaptable: metric value = 1
    - Support all missions with 0 additional cost
  - Mostly Adaptable: metric value = [0.5, 1)
    - Support all missions within switching cost threshold (Ct)
  - Partially Adaptable: metric value = (0, 0.5)
    - Within Ct, support all required missions and only part of optional
  - Non-Adaptable: metric value = 0
    - Within Ct, only support required missions
- Cost: plugin cost functions
- Capability:
  - Conform with ecosystem definition
  - Now enable it to be **computable** in industry

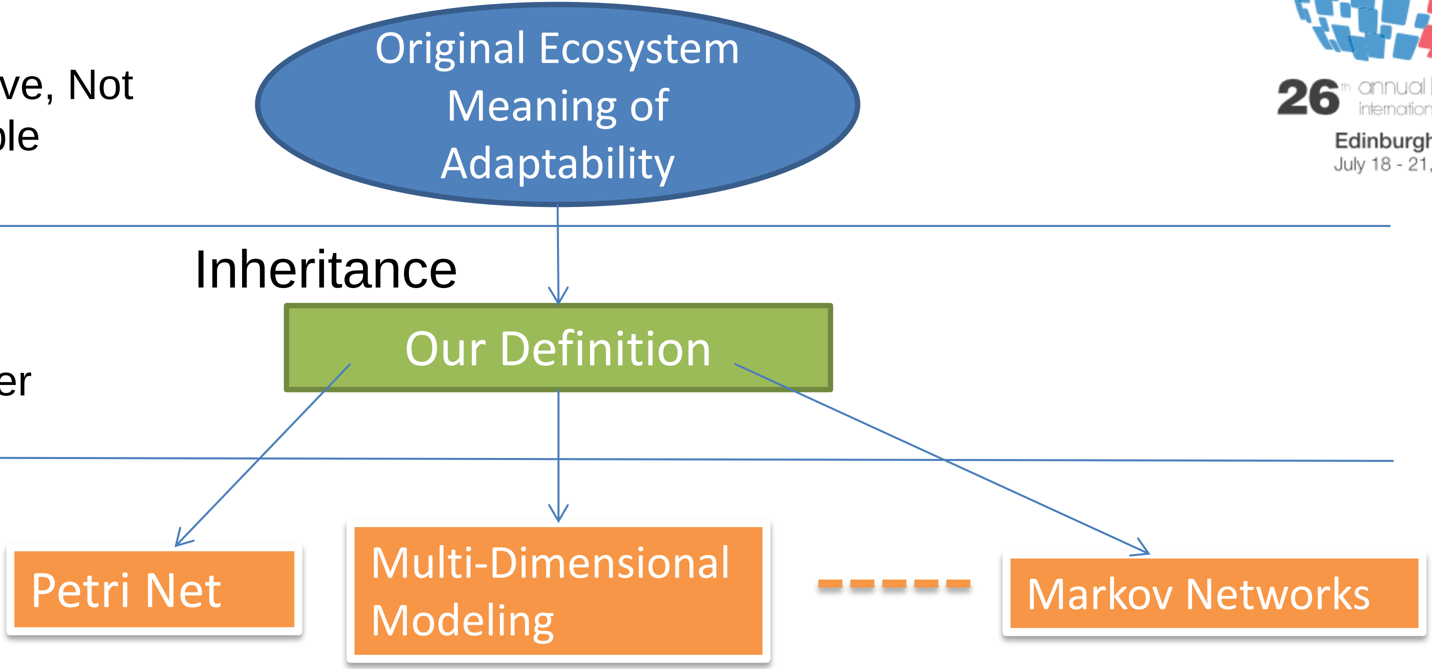
First introduced in DARPA Adaptive Vehicle Make (AVM) portfolio of programs, and also in: Zhu, H. "Designing Systems with Adaptability in Mind", Complex Systems Design & Management (CSD&M), Paris, 2015. Formally defined here.

Optimal Level of Abstraction

Abstract, Primitive, Not easily computable

Generic, Computable, Cannot be Higher

Specific Models (May not be Generic)



Example Case: Aircraft Engine

- Design Process:
  - Mission analysis
  - DSE generates all possible designs
  - Adaptability Tool outputs adaptability metric for each design

Engine Mission Evaluation Space

- Simplified

Table 2. Flight Mission Segments

	Baseline aircraft	Transatlantic jet	Commercial jet
One-engine-inoperative	True	True	True
Takeoff Gradient of Climb	1.2%	1.2%	1.2%
Climb Rate	1000ft/min	1500ft/min	1500ft/min
Cruise Range	700 nautical miles	4000 nautical miles	2000 nautical miles

Table 3. Considered Missions

1	takeoff low gradient	low climb rate	large cruise range	land	optional
2	takeoff low gradient	low climb rate	mid cruise range	land	required
3	takeoff low gradient	low climb rate	short cruise range	land	required
4	takeoff high gradient	low climb rate	large cruise range	land	optional
5	takeoff high gradient	low climb rate	mid cruise range	land	optional
6	takeoff high gradient	low climb rate	short cruise range	land	optional

Example Engine Cost Analysis

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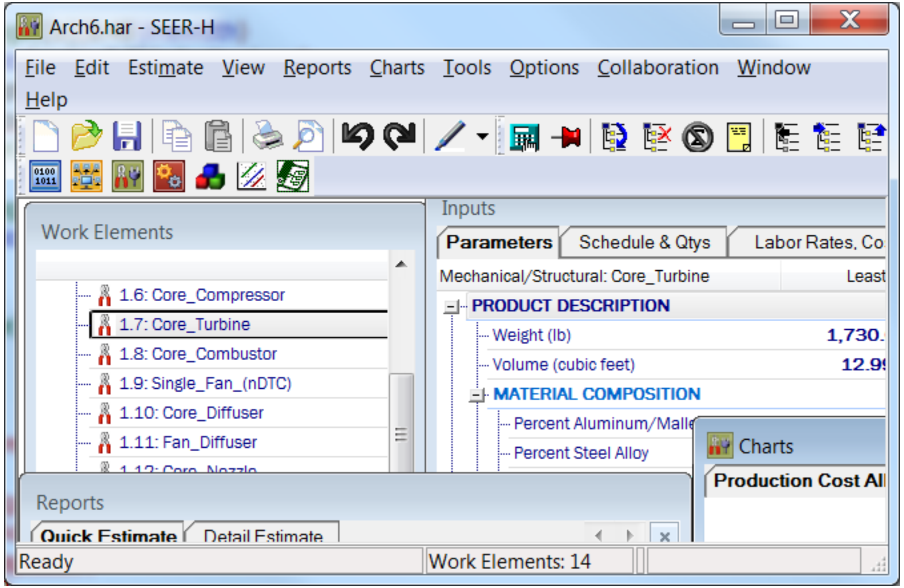
- Commercial tool (SEER) with Model-based Design*
- Reference:

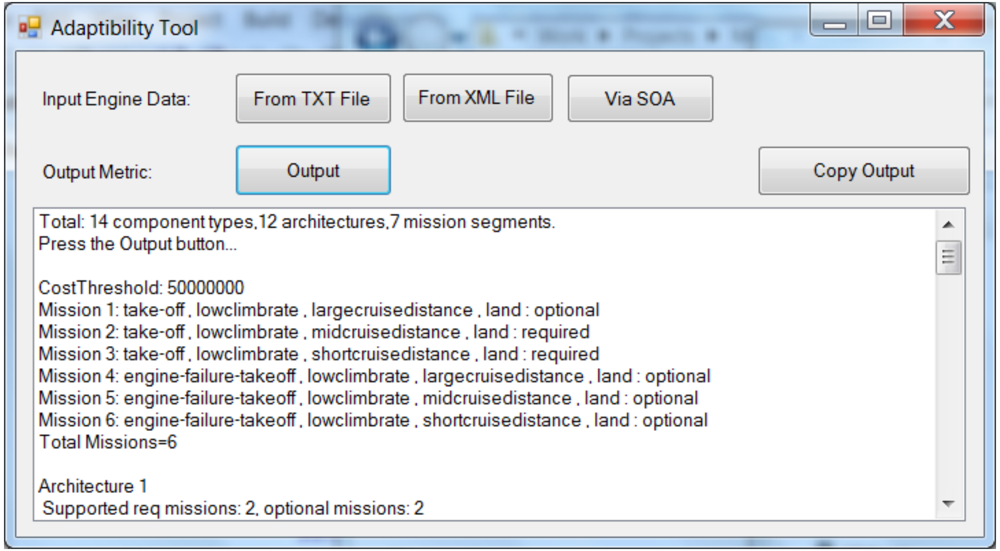
Zhu, H., et. al. “Exploring Early Stage Cost-Estimation Methods Using Off-the-Shelf Tools: A Case Study”, Complex System Design and Management (CSD&M) 2016.



*Courtesy Galorath Inc.

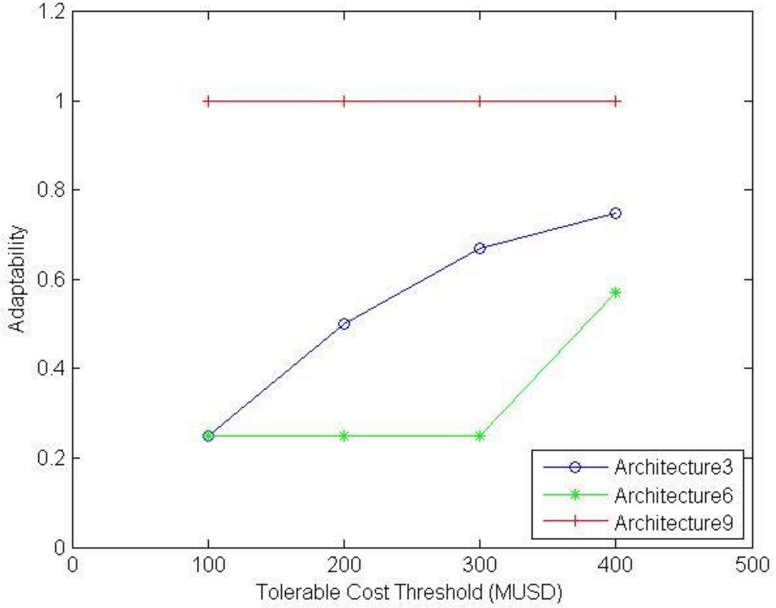
Adaptability Tool

- Receive design information from upstream tools
- Accepts multiple data formats
- Estimate Adaptability Metric for each design



Adaptability Metric Properties -1

- Variation with switching cost threshold



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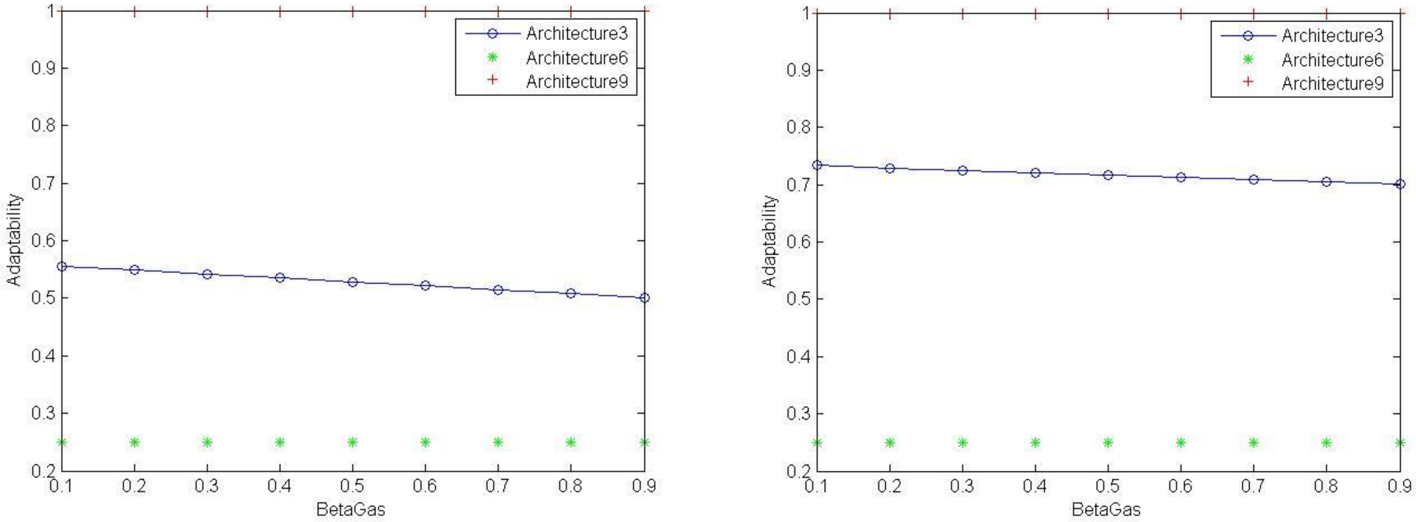
Adaptability Metric Properties -2

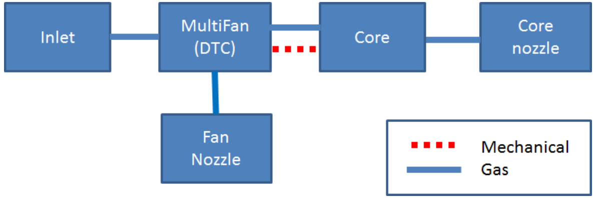
- Variation with switching cost functions



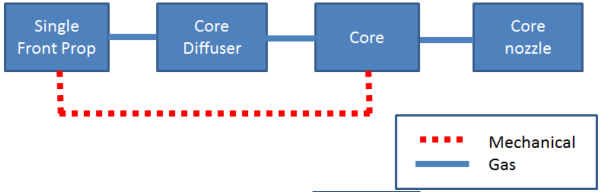
Adaptability Evaluation Output

- For each engine architecture

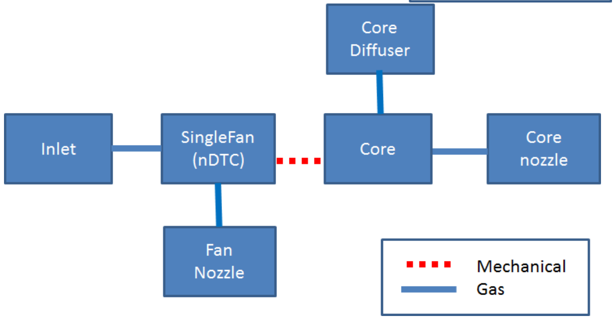
Architecture 3:
Supported req missions: 2, optional missions: 2
Best arch 11 within extra cost threshold: support required=2, opt=4
SWCost: 197 MUSD
Adaptability: 0.606



Architecture 6:
Supported req missions: 2, optional missions: 2
Best arch 6 within extra cost threshold: support required=2, opt=2
Adaptability: 0.25



Architecture 9:
Supported req missions: 2, optional missions: 4
Best arch 9 within extra cost threshold: support required=2, opt=4
SWCost: 0 USD
Adaptability: 1



Coincident with known finding in aerodynamics literature!

Summary and Conclusions

Mission-based adaptability's empirical mathematical properties are simple and indicate this formulation resolves issues with previous approaches:

- Use of mission space captures integral factors
  - Overcame previous issues: missing modeling elements leading to misleading measures
  - Avoided deviations from original ecosystem meaning
- Optimal level of abstraction
  - Generic, computable, unrestricted by concrete modeling techniques
- Framework allows evaluation of architectures
  - Architecture drives aspects of future designs useful for today's change dynamics
- Simplicity provides engineers rules of thumb for quickly evaluating the systems they design
  - Extensible with added sophistication