Evolvability-Related Options in Military Systems of Systems

Nicola Ricci, Donna H. Rhodes, and Adam M Ross

Massachusetts Institute of Technology

March 22, 2014

© 2014 Massachusetts Institute of Technology

Overview

- Intro
  - Motivation
  - Military SoS
- Framework
- Evolvability-related Options Examples
- Discussion & Next Steps

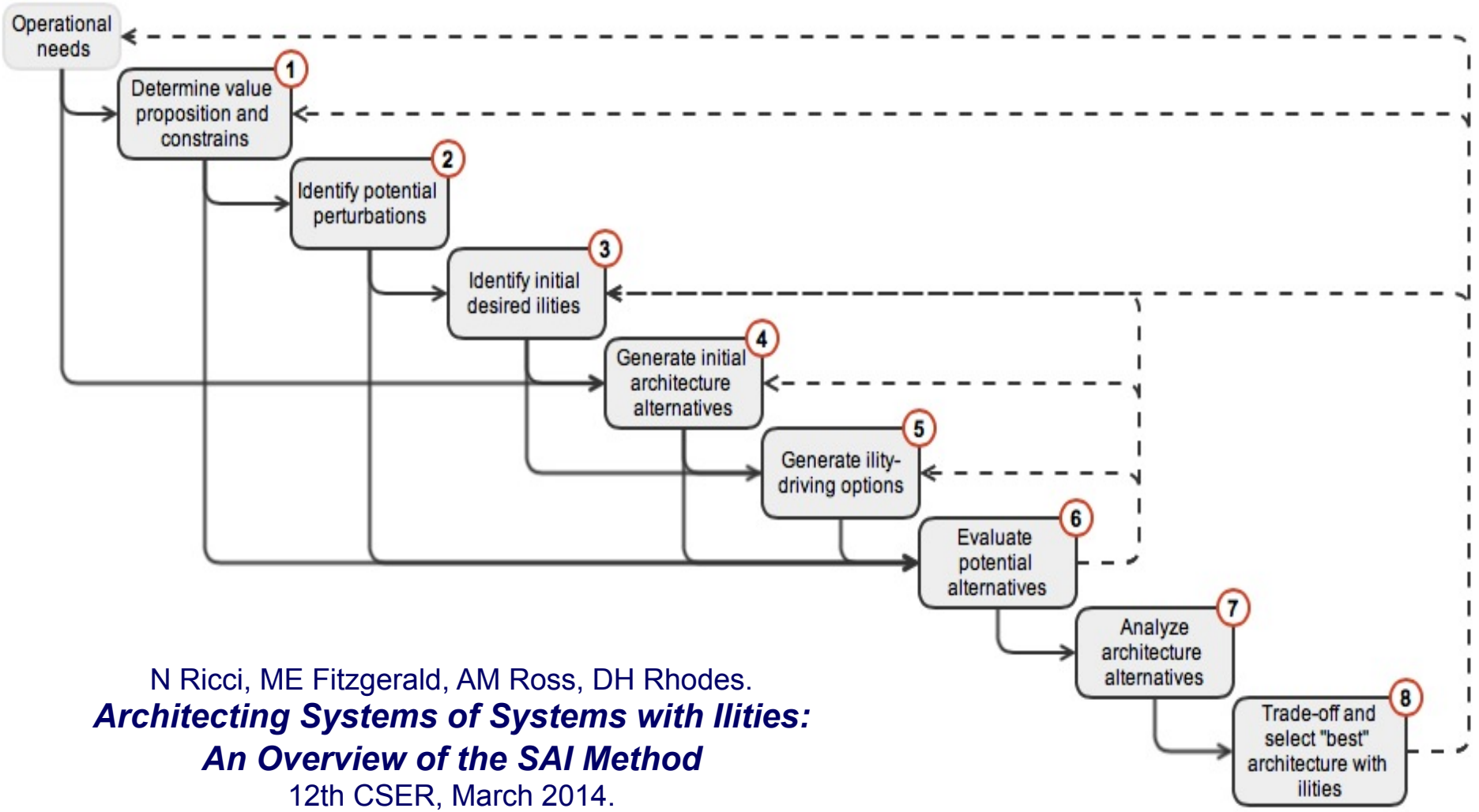
© 2014 Massachusetts Institute of Technology

Overview

- Intro
  - Motivation
  - Military SoS
- Framework
- Evolvability-related Options Examples
- Discussion & Next Steps

© 2014 Massachusetts Institute of Technology

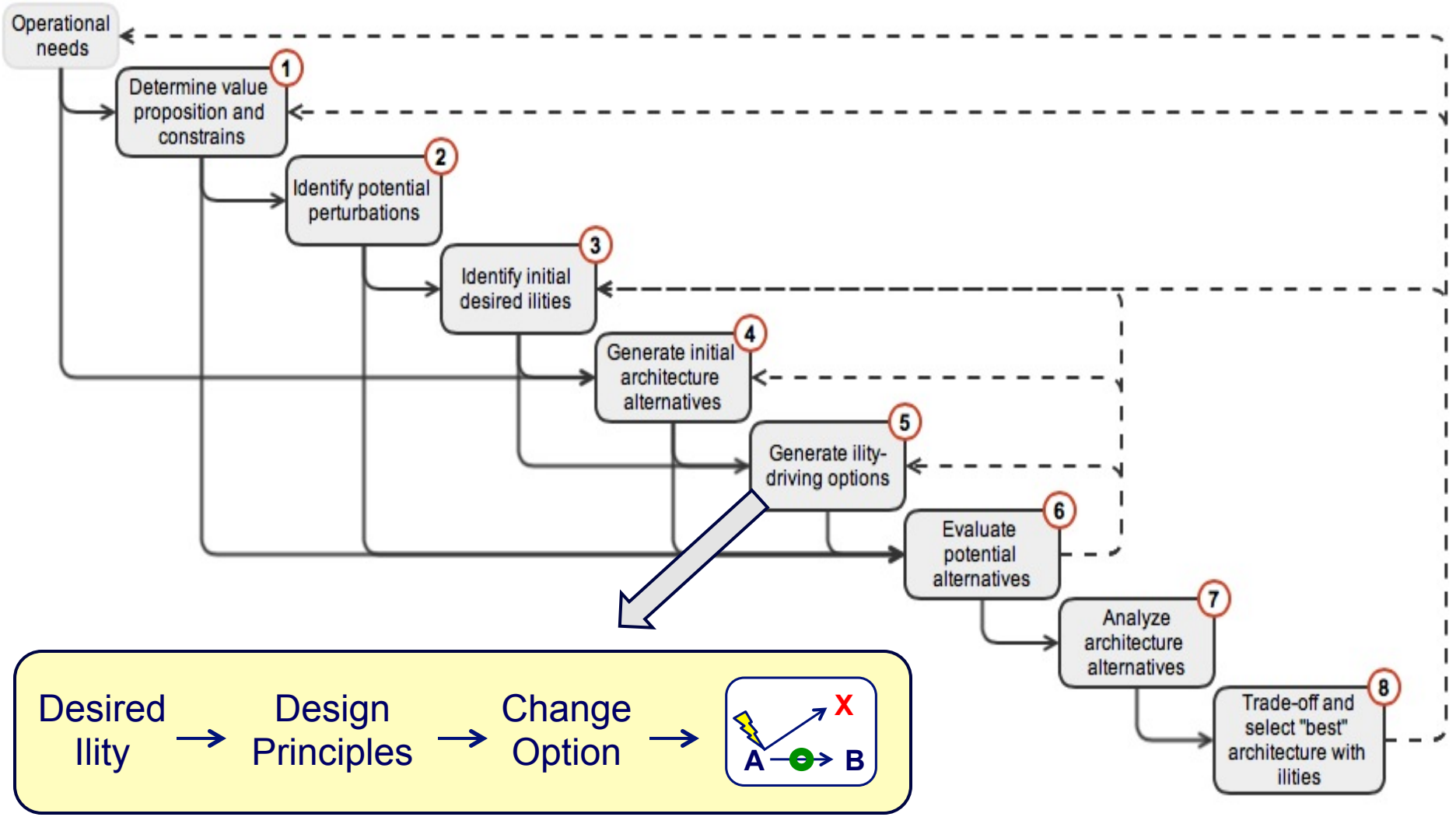
Context – MIT SAI Method



N Ricci, ME Fitzgerald, AM Ross, DH Rhodes.
Architecting Systems of Systems with Ilities: An Overview of the SAI Method
12th CSER, March 2014.

© 2014 Massachusetts Institute of Technology

Context – MIT SAI Method

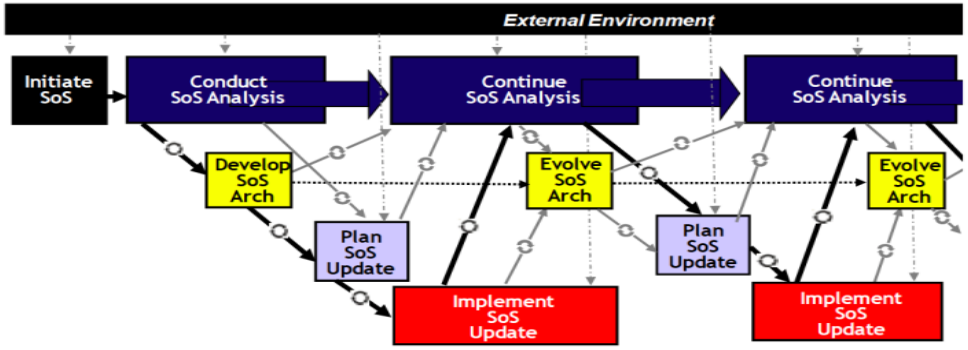


Desired Ility → Design Principles → Change Option →

© 2014 Massachusetts Institute of Technology

Motivation

SoS Engineering
- Ongoing analysis
- Periodic **re-architecting** activity
- Evolution increments



(Dahmann et al. – 2011)

What are ways in which evolvability can be embedded in the SoS?

The research aims to:

1) further **validate the usefulness of design principles** for architecting systems that possess desirable lifecycle properties such as ***evolvability***.
2) contribute **real-world examples** that architects may use to inspire specific design options for their system of interest.

Designing for evolvability enables systems architects to avoid architecture alternatives that are well-suited to present needs, yet unable to sustain value delivery over the lifespan of the SoS

© 2014 Massachusetts Institute of Technology

Military Systems of Systems
Mission SoS

BMDS

Ballistic Missile Defense System

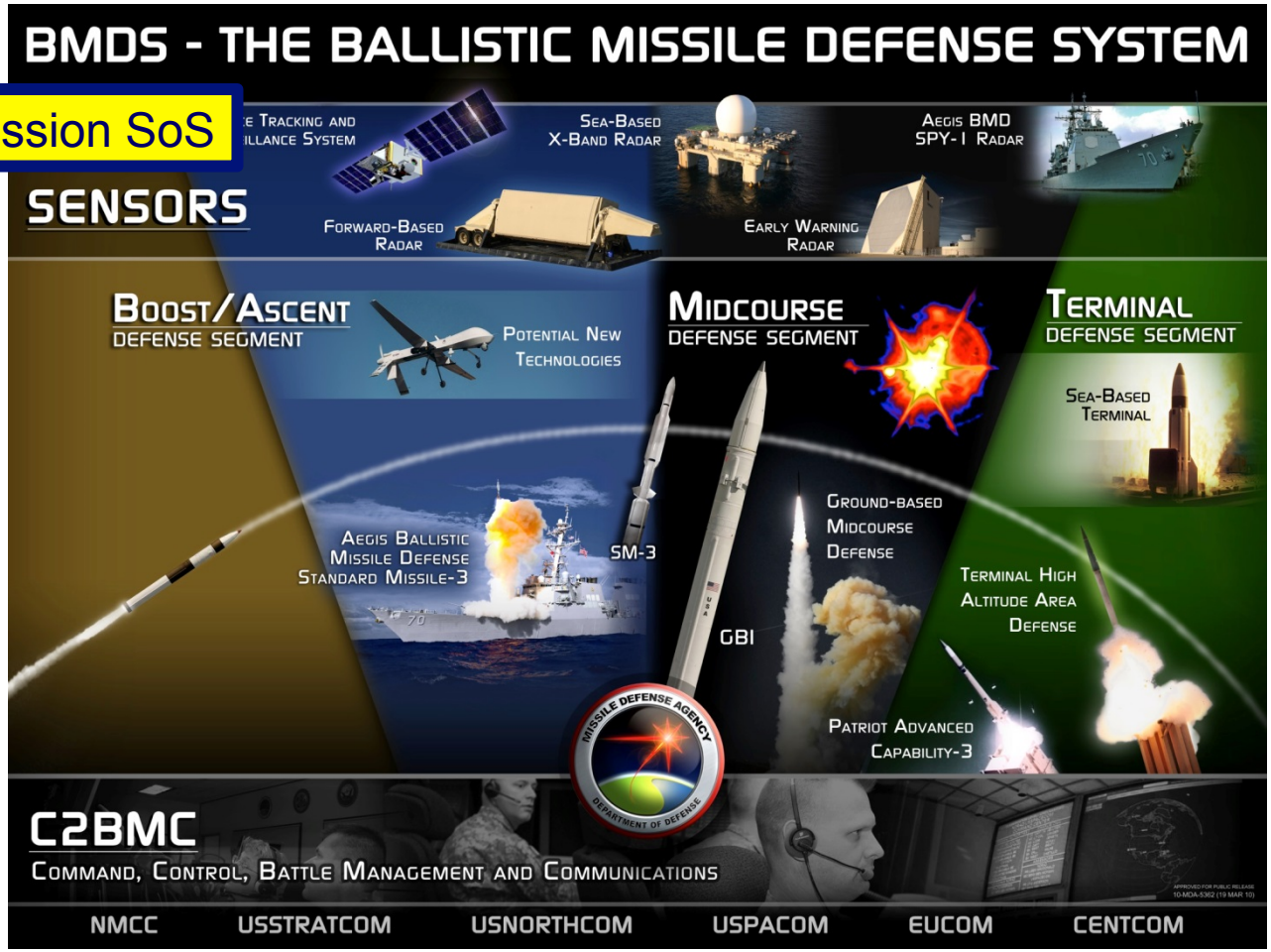
BCT

Brigade Combat Team Modernization

JIE

DISA - Joint Information Enterprise

Mission SoS



© 2014 Massachusetts Institute of Technology

Military Systems of Systems
Platform SoS

BMDS

Ballistic Missile Defense System

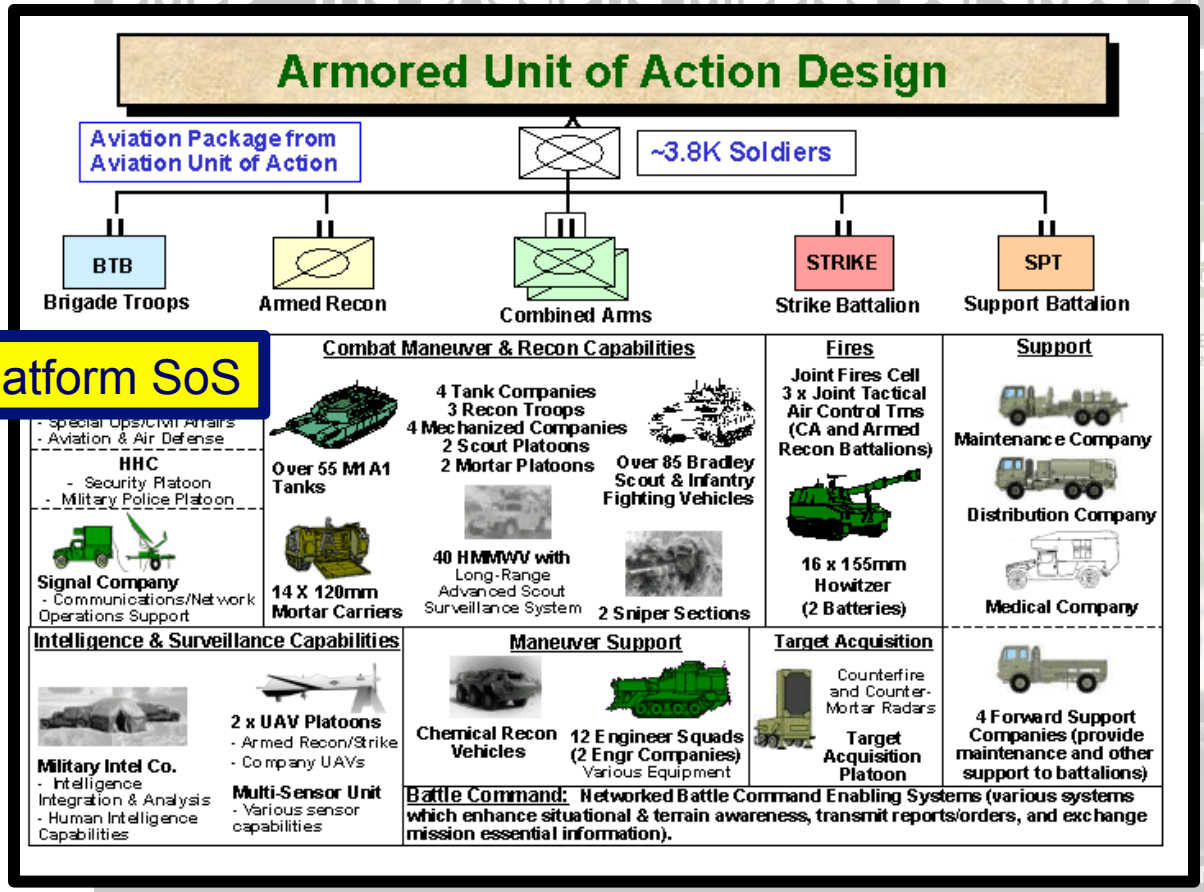
BCT

Brigade Combat Team Modernization

JIE

DISA - Joint Information Enterprise

Platform SoS



© 2014 Massachusetts Institute of Technology

Military Systems of Systems
IT SoS

BMDS

Ballistic Missile Defense System

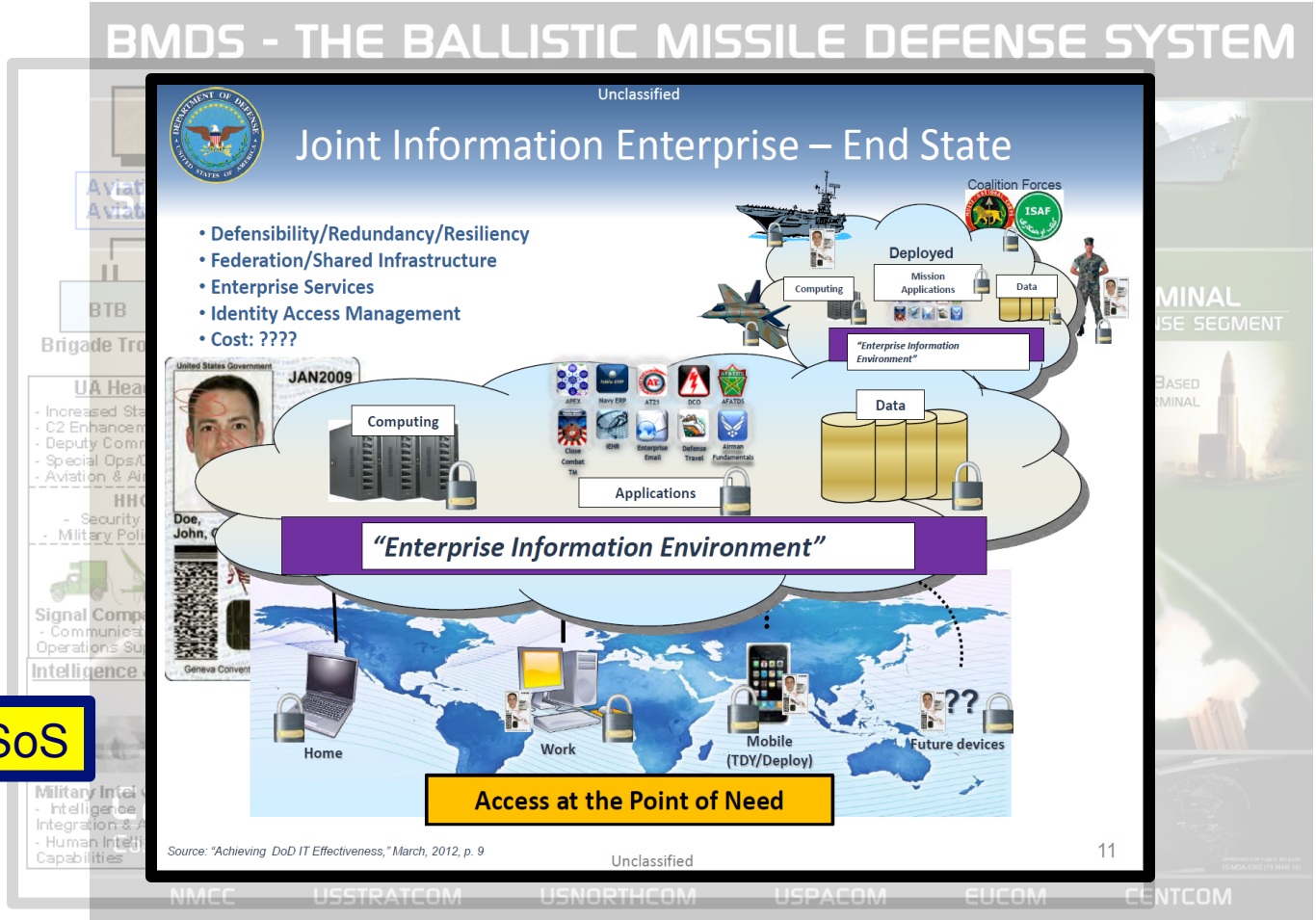
BCT

Brigade Combat Team Modernization

JIE

DISA - Joint Information Enterprise

IT SoS



© 2014 Massachusetts Institute of Technology

Overview

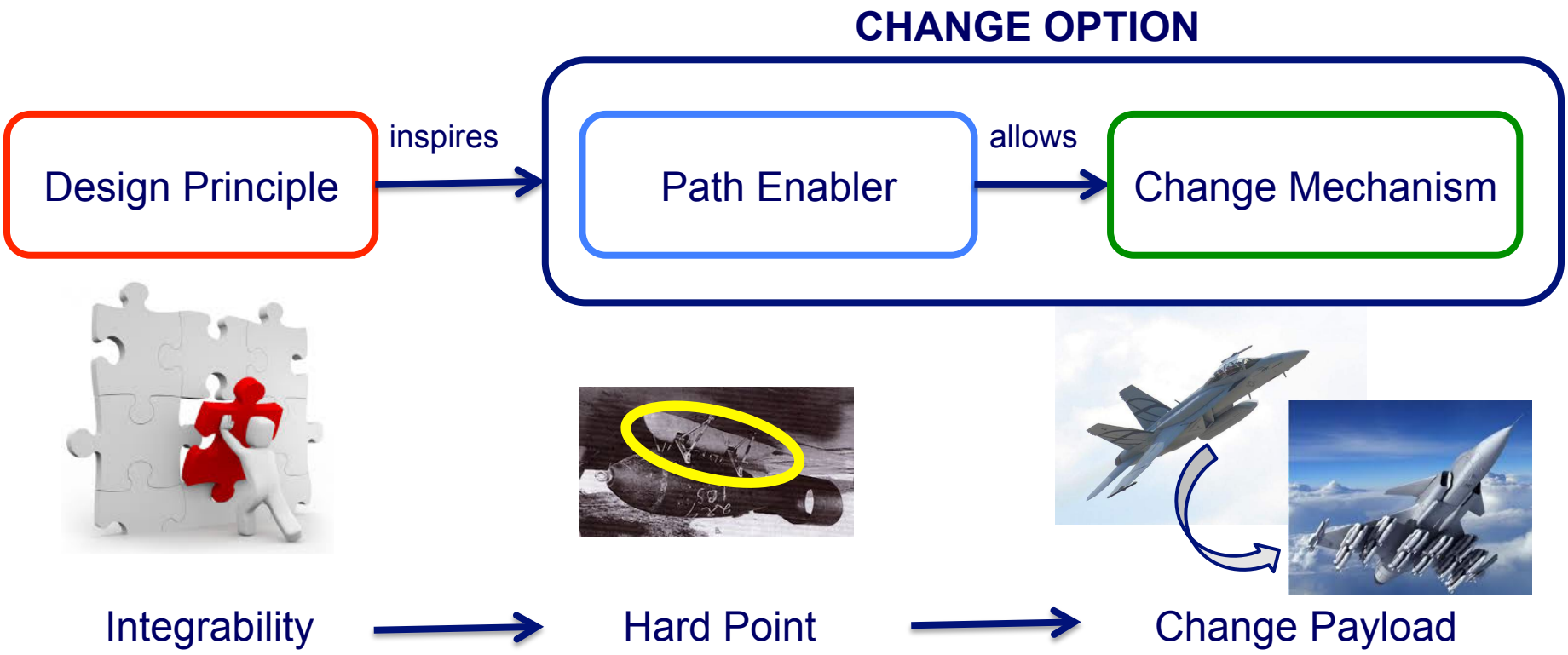
- Intro
  - Motivation
  - Military SoS
- Framework
- Evolvability-related Options Examples
- Discussion & Next Steps

© 2014 Massachusetts Institute of Technology

Descriptive Framework

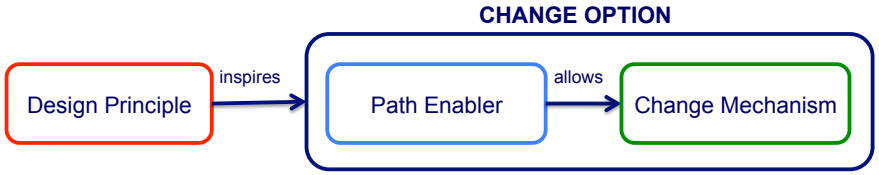
Evolutionary changes that SoS have undergone (or are undergoing) have been examined through the lenses of two constructs:

design principles and **change options**



© 2014 Massachusetts Institute of Technology

Design Principles

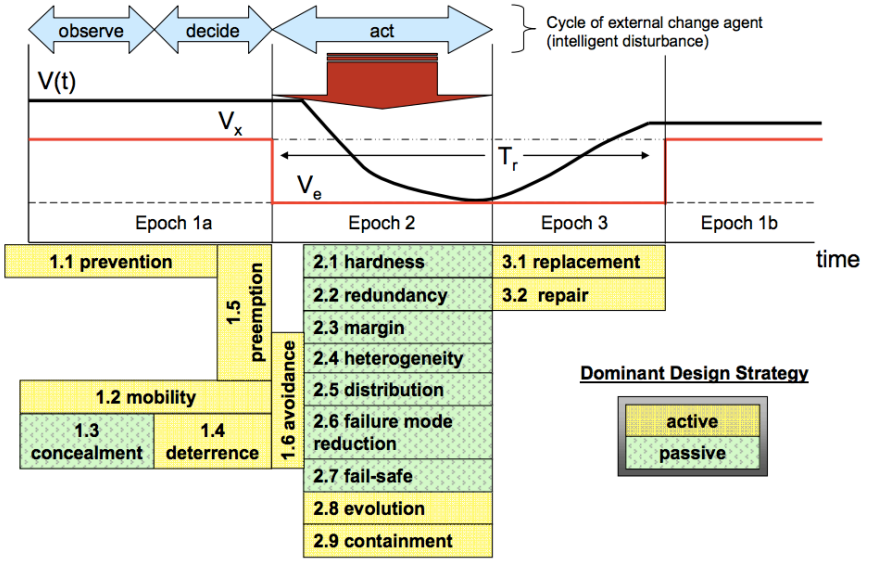


Design Principles:

"Guiding thoughts [for design] based on empirical deduction of observed behaviour or practices that prove to be true under most conditions over time"

(Wasson – 2006)

Desired Ility	Design Principle	
Survivability	Concealment	→ Option
Survivability	Hardness	→ Option
Evolvability	Targeted Modularity	→ Option
Evolvability	Decentralization	→ Option
Survivability	Heterogeneity	→ Option



(Richards, Ross, Hastings and Rhodes – 2009)

© 2014 Massachusetts Institute of Technology

Evolvability Design Principles
Strategies

Strategies
Design Principles

Leverage Ancestry	Employing successful design choices of assets, capabilities and/or operations from all prior generations of the system
Disruptive Architectural Overhaul	Re-architecting significant portions of the existing system or program at the same time in order to reduce the negative impact that making many smaller changes would have
Mimicry	Imitating or duplicating successful design choices of assets, capabilities and/or operations from other systems/domains for a similar purpose
Resourceful Exaptation	Repurposing assets or design choices from prior generations or other systems/domain in order to provide capabilities for which they were not originally selected

© 2014 Massachusetts Institute of Technology

Evolvability Design Principles
Structural

Structural
Design Principles

Leverage Ancestry	Employing successful design choices of assets, capabilities and/or operations from all prior generations of the system
Disruptive Architectural	Re-architecting significant portions of the existing system or program at the same time in order to reduce the

Decentralization	Distributing assets, capabilities and/or operations to appropriate multiple locations, rather than having them located in a single location
Targeted Modularity	Isolating parts of the system to reduce interdependencies in order to limit undesirable effects caused by either uncertainties or intentional changes
Integrability	Designing interfaces for compatibility and commonality to enable effective and efficient integration of upgraded/new system components and constituents
Reconfigurability	Creating intentional similarities in form and/or function of various system assets, capabilities, and/or operations to facilitate reuse or reallocation
Redundancy	Intentional duplication of selected assets, capabilities and/or operations to enable their future redistribution without compromising existing requirements
Scalability	Making design choices that allow scaling of resources and/or assets up or down in order to accommodate uncertainties and emergent needs
Margin	Architecting for intentional excess capacity in specific capabilities and/or operations to meet emergent needs without compromising existing requirements (i.e. meet or exceed future requirements)
Slack	Intentionally under-allocating or over-allocating specific available assets and/or resources in order to reserve excess capacity for accommodating uncertainties (i.e. prevent violation of constraints)

© 2014 Massachusetts Institute of Technology

Applying Design Principles
Architect's Intent

Structural Design Principles

Leverage Ancestry

Employing successful design choices of assets, capabilities and/or operations from all prior generations of the system

Disruptive Architectural

Re-architecting significant portions of the existing system or program at the same time in order to reduce the

Decentralization

Distributing assets, capabilities and/or operations to appropriate multiple

single location

endencies in order to limit

es or intentional changes

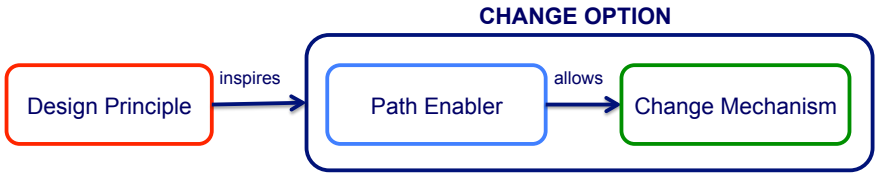
onality to enable effective and

Architect's Intent

- *Desire* to **Add New** Constituent System
- *Desire* to **Add More** of Existing Constituent System
- *Desire* to **Replace** or **Upgrade** Capabilities of Existing Constituent System
- *Desire* to **Add More** of Existing Function
- *Desire* to **Change** the Way in Which a Function is Performed
- *Desire* to Physically **Relocate** Resources/Capabilities

© 2014 Massachusetts Institute of Technology

Change Options



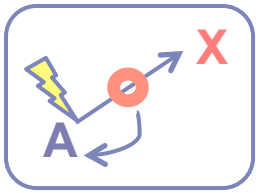
GENERALIZED OPTION

(Ricci et al. – 2013)

Resistance Option (RO)

- Path Inhibitor (PI)
- Resistance Mechanism (RM)

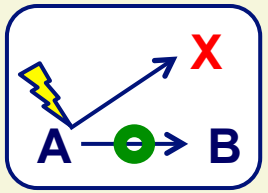
RO



X = bad state
A,B = acceptable state

Change Option (CO)

- Path Enabler (PE)
- Change Mechanism (CM)



CO

- The **change mechanism** is the **method** through which a system goes from state A to state B (e.g., *swapping payload on UAV*)
- The **path enabler** (i.e., a physical object, an action or a decision) is **what** gives the "option" of executing the change mechanism (e.g., *modular payload bay in original design*)

© 2014 Massachusetts Institute of Technology

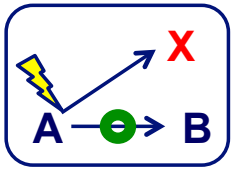
Overview

- Intro
  - Motivation
  - Military SoS
- Framework
- Evolvability-related Options Examples
- Discussion & Next Steps

© 2014 Massachusetts Institute of Technology

BMDS - *THAAD*

"Desire to add new constituent systems"



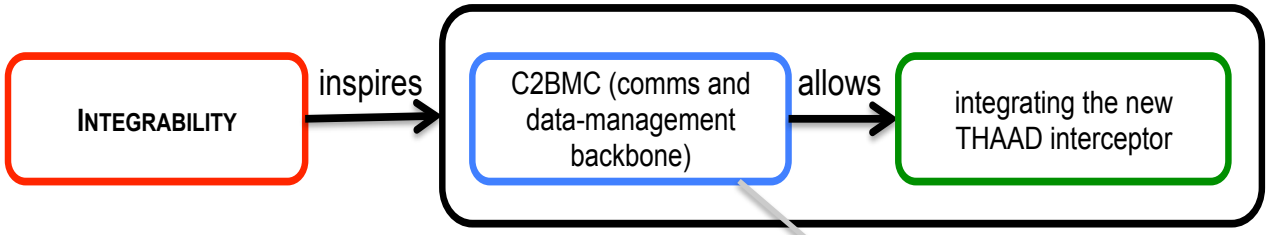
A

By 2004, BMDS used **PAC-3** and (when available) **SM-3** (sea-based) as short-term ballistic missile defense for the terminal segment.

Execute option

B

In 2008, **THAAD** (land-based) **was** tested and successfully **added** to the SoS for terminal defense segment.



Option

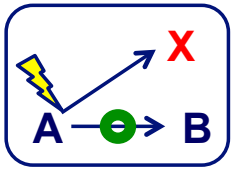
C2BMC → Purposely designed **path enabler**

- Tactical Datalink 16
- Extremely High Frequency (EHF)
- Global Engagement Manager (GEM)
- access control lists – ACLs

© 2014 Massachusetts Institute of Technology

BMDS – *Phase Adaptive Approach*

"Desire to physically relocate resources/capabilities"



A

As of 2009, BMDS had its interceptors (PAC-3, THAAD, SM-3 and GMD) on U.S. land (AK and CA). Communication and tracking capabilities were located in **space, U.S. territory and oceans** (SBX radar).

Execute option

B

U.S. was going to seek a Phased Adaptive Approach (PAA) to missile defense in Europe. The SoS was planned to be extended to **multiple bases in the Mediterranean Sea,** as well as some **European countries**

DECENTRALIZATION inspires SBX Radar, Aegis BMD ships, and relocation agreement allows Reallocating capabilities and resources to European bases

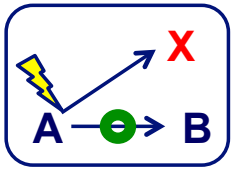
Option

In September 2009, President Barack Obama announced that the U.S. was going to seek a Phased Adaptive Approach (PAA) to missile defense in Europe, also thanks to U.S. long-standing relationship with some of the European countries.

© 2014 Massachusetts Institute of Technology

BMDS – *Phase Adaptive Approach*

"Desire to add more of existing function"



INTRODUCED

Option

Intentionally under-allocating or over-allocating specific available assets and/or resources in order to reserve excess capacity for accommodating uncertainties (i.e. prevent violation of constraints)

- **Phase 1** – deployed
- **Phase 2** – planned deployment date: 2015
  - Phase 2 will see interceptors taken onto land in the first "Aegis-Ashore" deployment in **Romania**.
- **Phase 3** – planned deployment date: 2018
  - Phase 3 will see the introduction of the second "Aegis-Ashore" site in **Poland** with another SPY-1 radar and 24 SM-3 missiles

In September 2009, President Barack Obama announced that the U.S. was going to seek a Phased Adaptive Approach (PAA) to missile defense in Europe, also thanks to U.S. long-standing relationship with some of the European countries.

© 2014 Massachusetts Institute of Technology

Overview

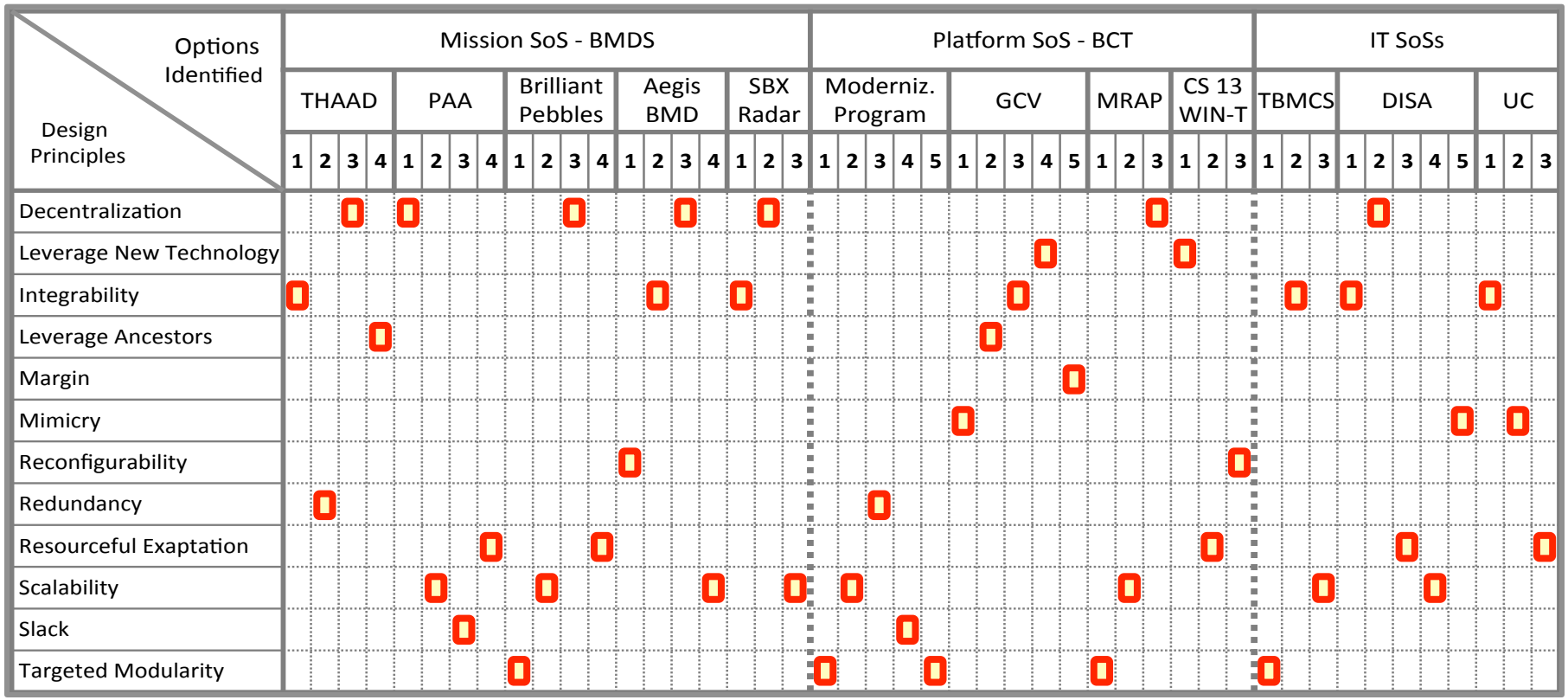
- Intro
  - Motivation
  - Military SoS
- Framework
- Evolvability-related Options Examples
- Discussion & Next Steps

© 2014 Massachusetts Institute of Technology

Progress Summary Matrix

Research in **early stage**, but some *preliminary patterns* are starting to be observed:

- **Every design principle was encountered** across all SoS types and evolution increments
- Some design principles appear to be **less frequent** than others



© 2014 Massachusetts Institute of Technology

Next Steps

- **Additional case examples** to further validate *evolvability* design principles
  - Long-term goal is to have enough data points to be able to discern *differences in use of design principles*
- SoS types discussed (mission, platform and IT) are **not collectively exhaustive**, but they are mutually exclusive
  - Gather evidence of usefulness of evolvability design principles for different SoS types
  - Future work will *expand the current set*.
- Ongoing research also looking at SoS evolvability with respect to *what* is specifically evolving
  - **SoS program** (e.g., FCS evolving to BCT Modernization)
  - The **SoS architecture** as a whole
  - **Constituent system** that impacts the evolvability of the SoS as a whole

© 2014 Massachusetts Institute of Technology

QUESTIONS?

Contact info:

Nicola Ricci – nricci@mit.edu
Donna H Rhodes – rhodes@mit.edu
Adam M Ross – adamross@mit.edu

MIT SEAri – seari.mit.edu

EVOLVABILITY-RELATED OPTIONS IN MILITARY SYSTEMS OF SYSTEMS

© 2014 Massachusetts Institute of Technology

Back-up Slides

© 2014 Massachusetts Institute of Technology

Motivation

The world in which Systems Engineers practice has undergone a significant metamorphosis over the past twenty years

- *Advent of the internet* → great increase in amount of resources available
- *Information travels at the speed of light* → instantaneous communication
- *High-speed computation* → Performance of very complex analyses

Systems are subject to highly **dynamic operational environments**

- A multitude of exogenous uncertainties can impact a system
  - *Geo-political shifts* (e.g., policy/regulation changes)
  - *Disruptive technologies* (e.g., advent of GPS)
  - *Market variations* (e.g., price &demand variations)
- Unanticipated shifts in stakeholder needs
  - Change of *preferences*
  - Change of *mission objectives*
- Systems of Systems
  - *Managerial and operational independence*
  - *Continually evolving*

If focused solely on the present state of the world, engineers may encounter the problem of designing systems that may not be well positioned in the future, forced to operate in contexts for which they were not conceived, and delivering capabilities no longer of interest to stakeholders.

© 2014 Massachusetts Institute of Technology

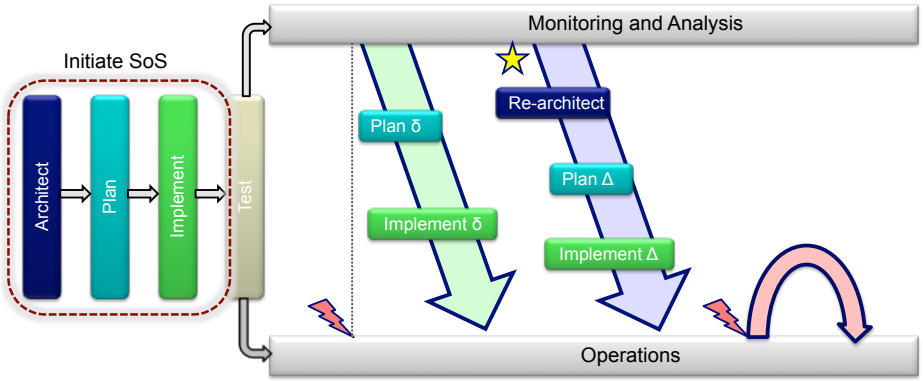
Ilities

- Modern **ilities** (e.g. flexibility) are one response to mitigate the impact of dynamic complexities on system value over time.

Ilities are *"properties of engineering systems that often manifest and determine value after a system is put into initial use. Rather than being primary functional requirements, these properties concern wider impacts with respect to time and stakeholders."*

(de Weck, Ross, and Rhodes – 2012)

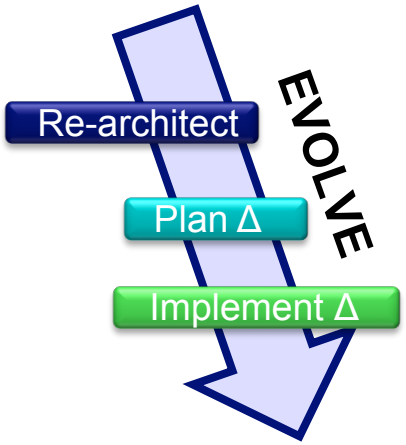
- The purpose of any system is to provide some level of value to its stakeholders, whose interest is that system keep providing value throughout the expected lifecycle
- System designers attempt to make systems that can provide value in spite of exogenous perturbations → i.e., devise value sustainment strategies



(Ricci, Ross, and Rhodes – 2013)

© 2014 Massachusetts Institute of Technology

Evolvability



BIOLOGY

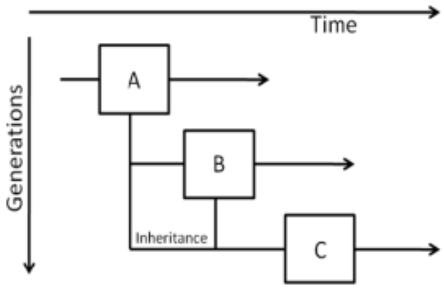
"the ability of a population to both generate and use genetic variation to respond to natural selection"
(Colagrave N, Collins S. – 2008)

SYSTEMS ENGINEERING

"evolvable systems as being able to accommodate adaptive variations in some locales without changing the behaviour of subsystems in other locales"
(Sussman GJ – 2007)

SoS ENGINEERING

"ability of the architecture to handle future upgrades "
(Butterfield ML, Pearlman JS, Vickroy SC – 2008)



Evolution of SoSs over time

EVOLVABILITY: *The ability of an architecture to be inherited and changed across generations [over time]*

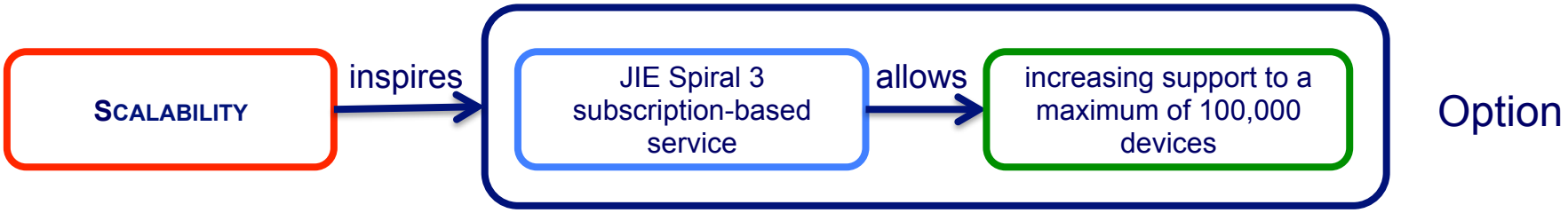
(Beesemyer JC – 2012)

- Collected different concepts and ideas regarding evolvability **from various fields** (from biology, to technology innovation, to systems engineering)
- Definition of evolvability rests upon a **key distinction among systems' architecture, design and instance**

© 2014 Massachusetts Institute of Technology

DISA – *Joint Information Enterprise Mobile Solutions*

INTRODUCED



- The mobility (subscription-based) services used – unclassified or classified – are **scalable** to accommodate increasing (or decreasing) numbers of users.
  - As such they represent a **path enabler**
  - The SoS architecture uses commercial carriers for providing subscription-based services. Commercial carriers and other unclassified access networks provide **controlled connectivity** between users and mobile enterprise.
- Operational capability is expected to **grow** with subscription-based services **up to 100,000 devices** – starting from 1,500 initial devices.

© 2014 Massachusetts Institute of Technology