Systems Engineering Advancement Research Initiative

Architecting Systems for Value Robustness: Research Motivations and Progress

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Massachusetts Institute of Technology

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Topics

Value Robustness Defined

Research Motivations

Research Landscape

Six Areas of Research

- Implications for Practice

Future Directions

- Newest area of research

Research Engagement and Transition

MIT SEAri Mission

Advance the theories, methods, and effective practice of systems engineering applied to complex socio-technical systems through collaborative research

Value Robustness

Value robustness is the ability of a system to continue to deliver stakeholder value in the face of changing contexts and needs.

Ross 2006

"Personal Banking System"

ATM Network, ATMs, Bank Card

Changes in Context

– Withdraw funds in Boston at morning
– Withdraw funds in Montreal in evening

Changes in Need

– Withdraw funds
– Deposit funds

Changing Expectations

– Get US dollars in Boston
– Get Canadian dollars in Montreal

Value Robustness

A *value robust system* is one perceived to be successful by stakeholders who continue to receive value from the system over time.

Ross and Rhodes 2008

Value Robustness Strategy

Changing Needs

Changing Expectations

Changing Context

Value Robustness Strategy

- Versatile design such that change is not needed
  (passive value robustness)
- Highly changeable
  (active value robustness)

Research Motivations

The role of a good designer is less about technical achievement than it is about achieving value creation and sustainment

Understanding how people perceive value is fundamental to creating valuable systems

Static assumptions – captured in requirements – are insufficient for a valuable system as needs and perceptions shift with time

Systems Engineering for value robustness means developing systems/system-of-systems that are:

- Capable of adapting to changes in mission and requirements
- Expandable/scalable
- Designed to accommodate growth in capability
- Able to reliably function given changes in threats and environment
- Effectively/affordably sustainable over their lifecycle
- Easily modified to leverage new technologies

Reference: Rhodes, D., *Workshop Report – Air Force/LAI Workshop on Systems Engineering for Robustness, July 2004, http://lean.mit.edu*

Value Robustness

Value robustness is the ability of a system to continue to deliver stakeholder value in the face of changing contexts and needs.

Architecting value robust systems requires new methods for exploring the concept tradespace, as well as for decision making.

Research!

Also needed are architecting principles and strategies, an approach for the quantification of changeability, and an improved ability for architects and analysts to classify value for purposes of dialogue and implementation

Research Landscape

A research landscape is the overall mental model under which research is formulated, performed, and transitioned to practice

1. **Provides context for the research agenda, methods, and specific projects**
2. **Determines a community of interest**
3. **Opportunities for/constraints on funding sources and sponsors**
4. **Significantly influences research outcomes and impact**

Engineering systems is a field of study taking an integrative holistic view of large-scale, complex technologically enabled systems with significant enterprise level interactions and socio-technical interfaces

Engineering Systems Emphasizes Four Perspectives

1. **Broad interdisciplinary perspective**

2. **Incorporation of systems properties or "ilities"**

3. **Enterprise perspective**

4. **A complex synthesis of stakeholder perspectives**

Engineering Systems

An academic field of study taking an integrative holistic view of large-scale, complex technologically enabled systems with significant enterprise level interactions and socio-technical interfaces

Engineering Systems Emphasizes Four Perspectives (1)

A very **broad interdisciplinary perspective**, embracing technology, policy, management science, and social science

- Value is examined from many different perspectives
- Value may be characterized beyond typical product oriented attributes

Engineering Systems Emphasizes Four Perspectives (2)

An **intensified incorporation of system properties or "ilities"** (e.g., sustainability, survivability, flexibility) in the design process

.

- Important first use properties for value delivery
- Strategies can be derived for designing for these properties

Engineering Systems Emphasizes Four Perspectives (3)

Enterprise perspective, acknowledging interconnectedness of product system with enterprise that develops and sustains it

.

- Enterprise and environment as context
- Designing for value robustness larger than product alone

Engineering Systems Emphasizes Four Perspectives (4)

Complex synthesis of stakeholder perspectives, of which there may be conflicting and competing needs which must be resolved to serve the highest order system (system-of-system) need

- Elaboration of stakeholder perspectives
- Quantitative basis for comparison
- Enables dialogue toward shared value proposition

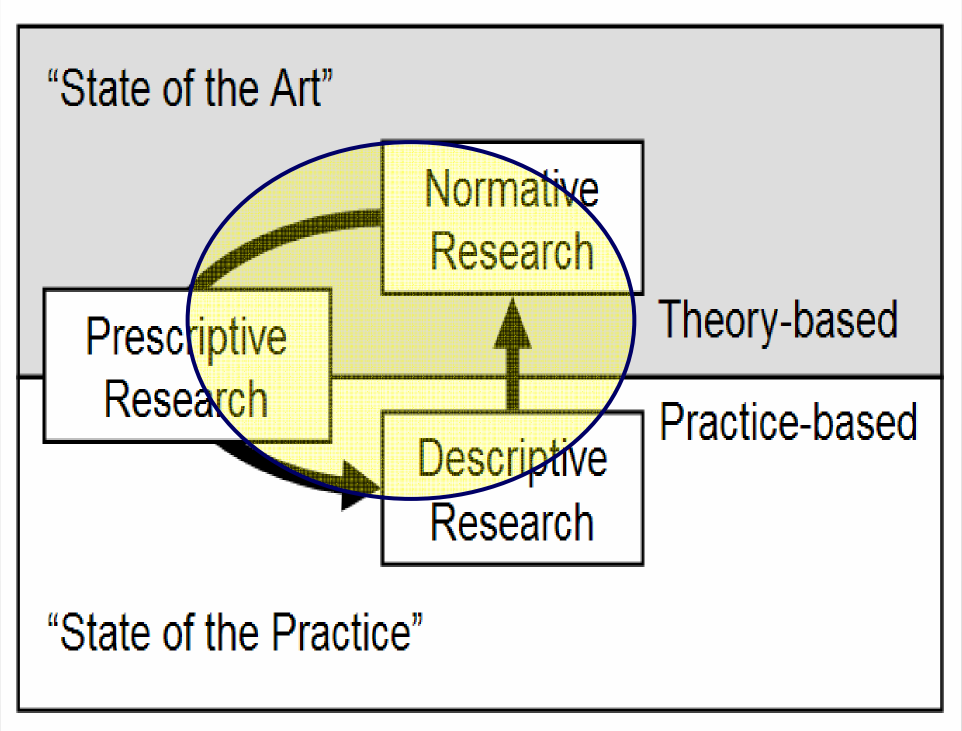
Underlying Research Structure

Prescriptive methods seek to advance state of practice based on sound principles and theories, as grounded in real limitations and constraints

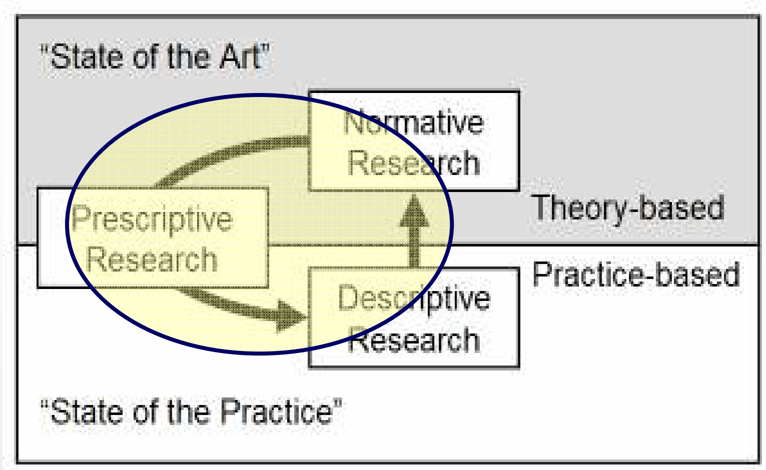
- Normative research: identify principles and theories -- "should be"
- Descriptive research: observe practice and identify limits/constraints

RESEARCH PORTFOLIO

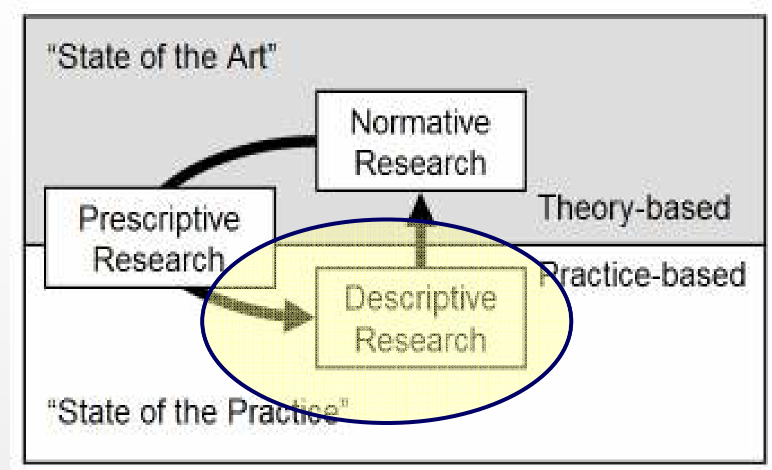
1. **Socio-Technical Decision Making**
2. **Designing for Value Robustness**
3. **Systems Engineering Economics**
4. **Systems Engineering in the Enterprise**
5. **Systems Engineering Strategic Guidance**



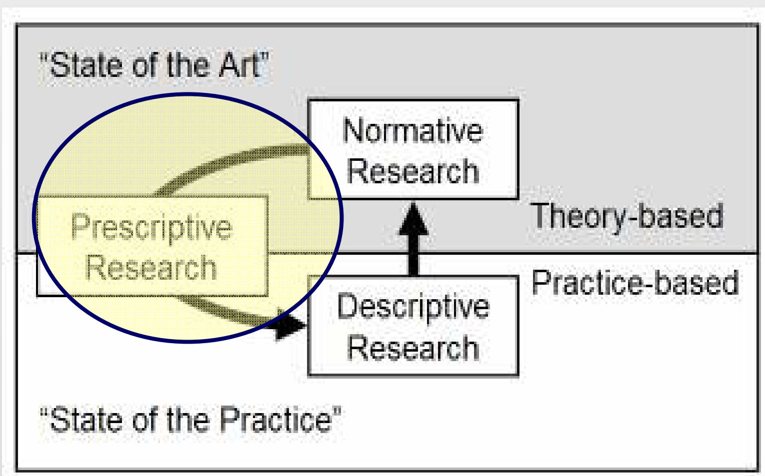
Value Robustness Research Projects Mapped to Structure



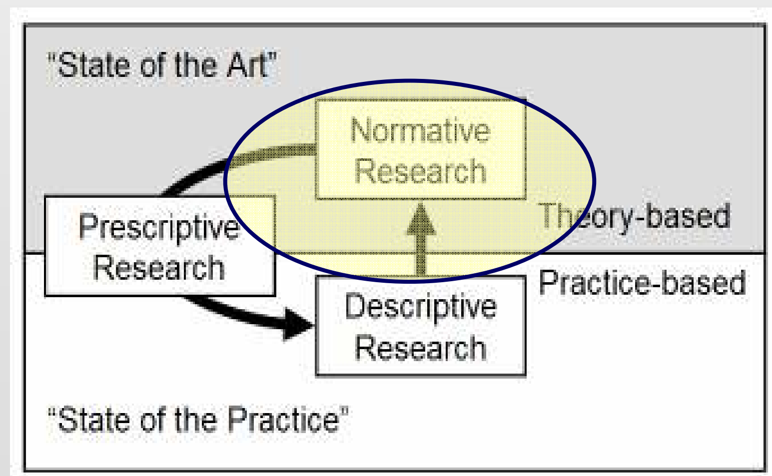
Tradespace Exploration Method Validated in Real World Cases



Codified Successful Practices based on Empirical Studies



Tradespace Exploration Guidance



Theory Development with Modeling

Six Areas of Research

How do stakeholders perceive value?	(1) Attribute Class Spectrum
How can stakeholders have a dialogue on value?	(2) Change Taxonomy
How can value robustness be quantified?	(3) Metrics for Changeability
How can value robust systems be identified?	(4) Tradespace Exploration Method
How can we architect for value robustness?	(5) Architecting for "Ilities"
What about systems of systems?	(6) SoS Tradespace Exploration

Attribute Class Spectrum

Articulated, Unarticulated and Latent Value

Research focuses on approach of ensuring system designers account for future changed value perceptions by thinking about these attributes according to ease by which system can display them

Elicitation of Value:

Design of value robust systems involves elicitation of stakeholder values through direct means as well as observations

A.M Ross and D.H. Rhodes, Using Attribute Classes to Uncover Latent Value during Conceptual Systems Design, IEEE Systems Conferences, Montreal, CA, April 4-5, 2008

Attribute Class Spectrum

Implications for Systems Engineering Practice

1. Better decisions by improving the practice through more rigorous constructs that characterize system attributes and their costs
2. Ability to more effectively explore unarticulated and latent value can uncover essential needs and desires of stakeholders early in the process
3. Observation during experimentation or early use of how stakeholders leverage latent value can be an important source of innovation

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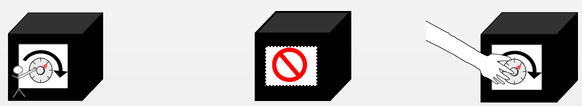
Change Taxonomy

Changeability

Change type

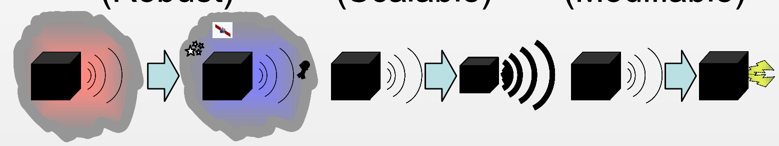
Change Agent

- Internal (Adaptable)
- None (Rigid)
- External (Flexible)



Change Effect

- None (Robust)
- Parameter level (Scalable)
- Parameter set (Modifiable)



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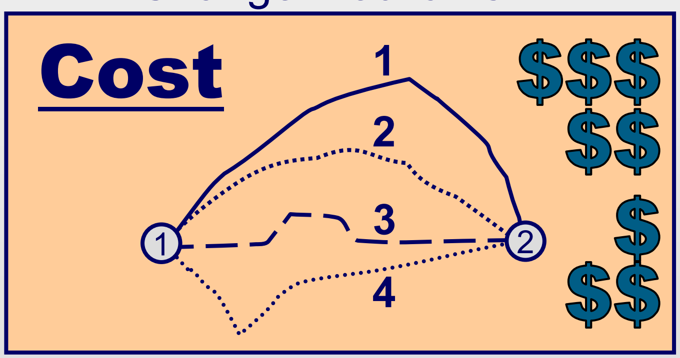
Ways to change

Change Mechanism



Number of mechanisms is a partial measure of changeability

Now that changeability is defined… how can it be used to evaluate systems?

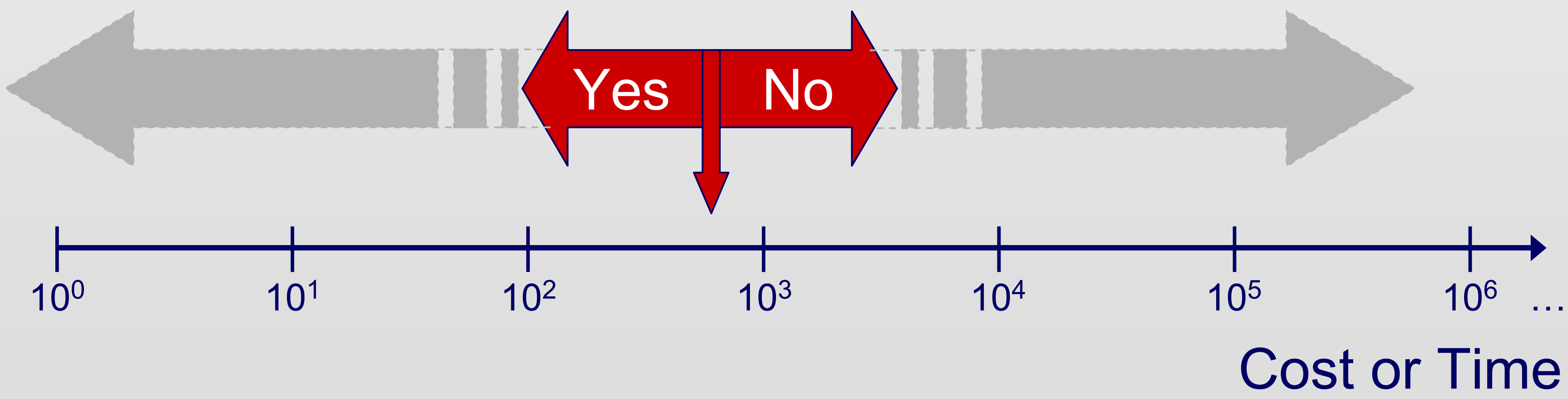
Change Taxonomy

The Question: So is the system ______________?

(Flexible, Adaptable, Robust, Scalable, Modifiable, Changeable, Rigid, etc…)

The Answer: It depends!

The question is fundamentally subjective. Really the question is not whether (yes/no), but to what extent (how much does it "cost")?



Change Taxonomy

Implications for Systems Engineering Practice

1. Remove ambiguity and provide quantitative description of “ilities” to improve acquisition and development
2. Potential to lead to the normative specification of the “ilities” as a basis for prescriptive guidance
3. Taxonomy provides a common lexicon for stakeholder dialogue

A.M Ross, D.H. Rhodes, and D.E. Hastings, Defining Changeability: Reconciling Flexibility, Adaptability, Scalability and Robustness for Maintaining Lifecycle Value, INCOSE International Symposium, June 2007

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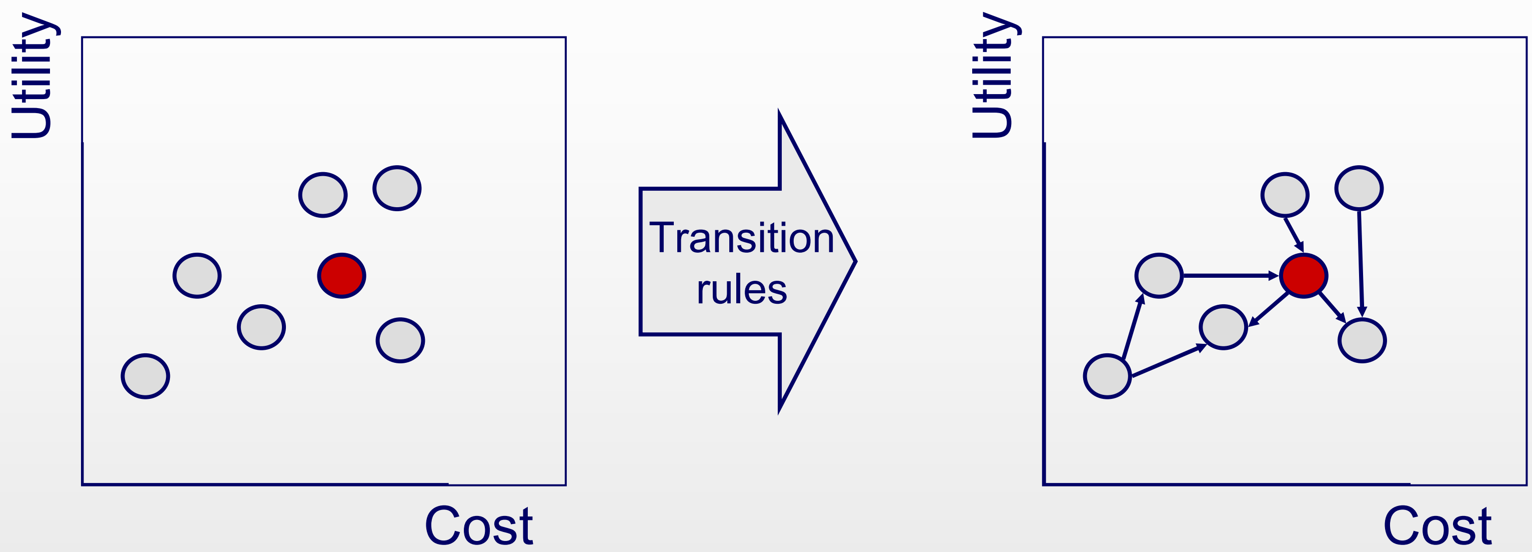
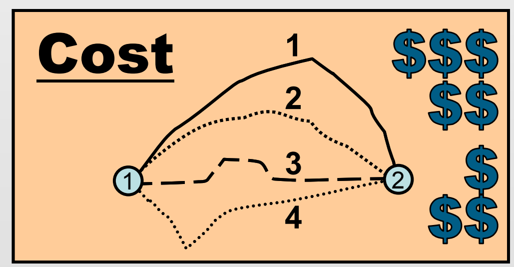
Tradespace Networks



Tradespace designs = nodes

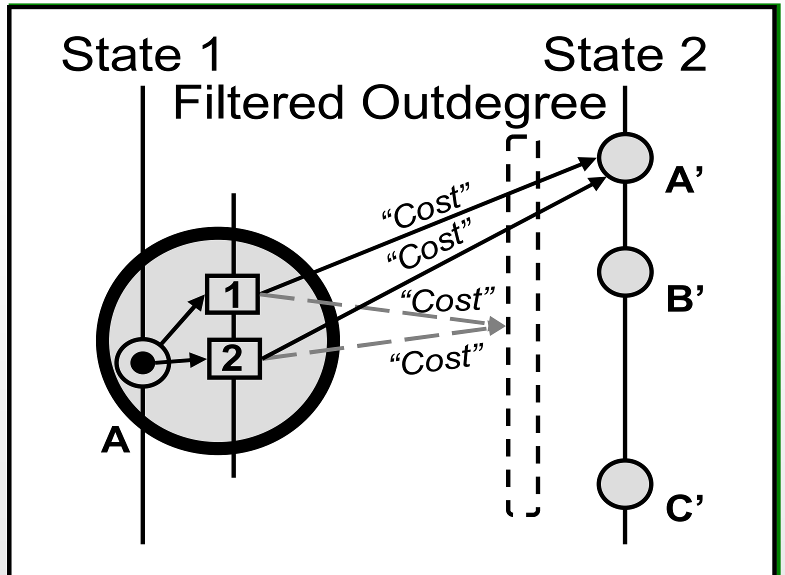
Applied transition rules = arcs



Transition rules are mechanisms to change one design into another
The more outgoing arcs, the more potential change mechanisms

Metrics for Changeability

- Ross (2006) defines filtered outdegree as quantification of subjective changeability
- Outdegree of a design is the number of transition paths from the design to possible future state designs
- Imposing a filter on the outdegree determines the only viable transition paths
- Changeability differs across decision makers based on thresholds for acceptable transition cost



Filtered Outdegree

A measure of changeability of a design as related to a decision maker's subjective threshold for acceptable "cost" of change

Metrics for Changeability

Implications for Systems Engineering Practice

1. Construct for quantitatively assessing changeability of candidate designs in a tradespace
2. Provides designers with analytic construct for making design decisions
3. Contributes to composing repeatable and verifiable requirements for changeability

Is Design A more changeable than Design B?

At what cost?

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Value-Based Conceptual Design Through Tradespace Exploration

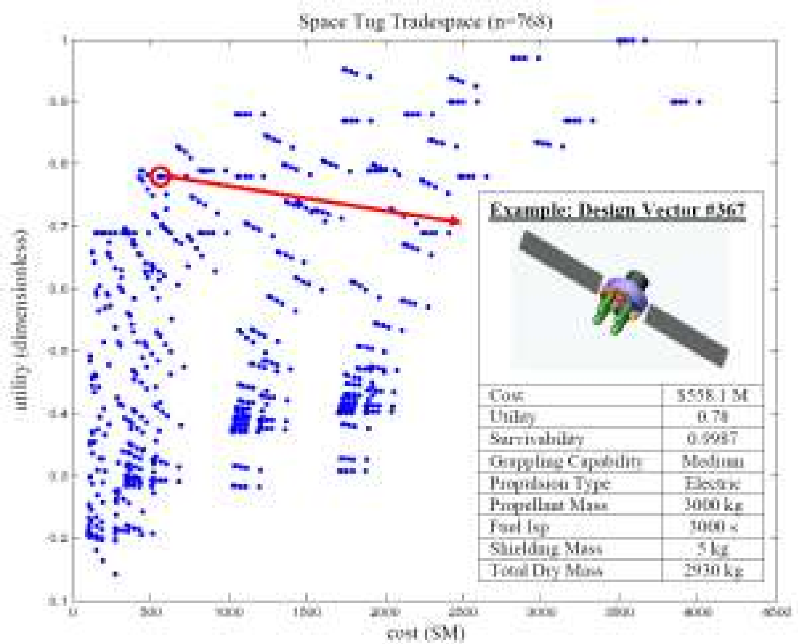
Value is a measure of net benefit specified by a stakeholder

Value-centric perspective enables unified evaluation of technically diverse system concepts

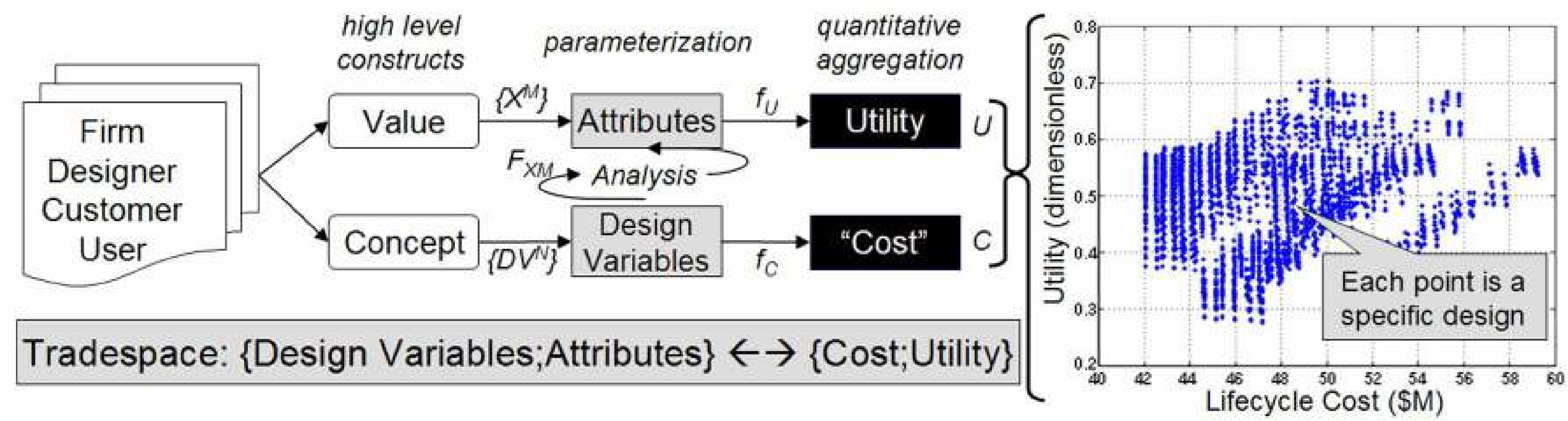
Operationalized through the application of decision theory to engineering design -- quantifies benefits, costs, and risks

Tradespace exploration uses computer-based models to compare thousands of architectures

- **Avoids limits of local point solutions**
- **Maps decision maker preference structure to potential designs**



Architecture Tradespace



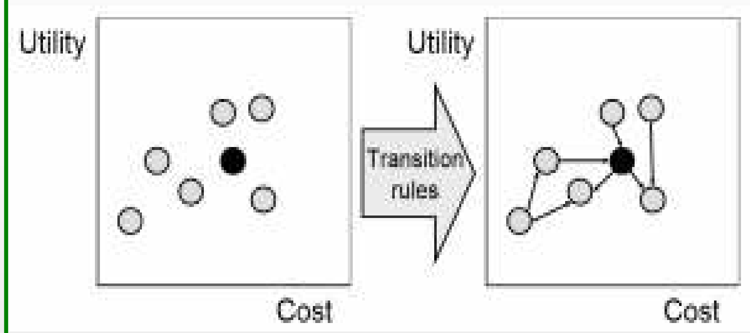
An architecture tradespace is typically represented by a plot of architecture and design options in terms of utility versus cost

Ross, A.M. and Hastings, D.E., "The Tradespace Exploration Paradigm," INCOSE International Symposium 2005, Rochester, NY, July 2005.

Ross, A.M., Rhodes, D.H., and Hastings, D.E., "Defining Changeability: Reconciling Flexibility, Adaptability, Scalability, Modifiability, and Robustness for Maintaining Lifecycle Value," *Systems Engineering*, Vol. 11, No. 4, December 2008, preprint http://seari.mit.edu

Dynamic Multi-Attribute Tradespace Exploration Method

- Traditional trade studies insufficient for comprehensive conceptual design
- Tradespace exploration adds computer-based parametric models and simulations enabling comparison of hundreds/ thousands of architectures
- Can be applied to static case, but **higher benefit through dynamic exploration**
- Design transition rules are applied to consider if and how to transition from one design to another



Dynamic Tradespace

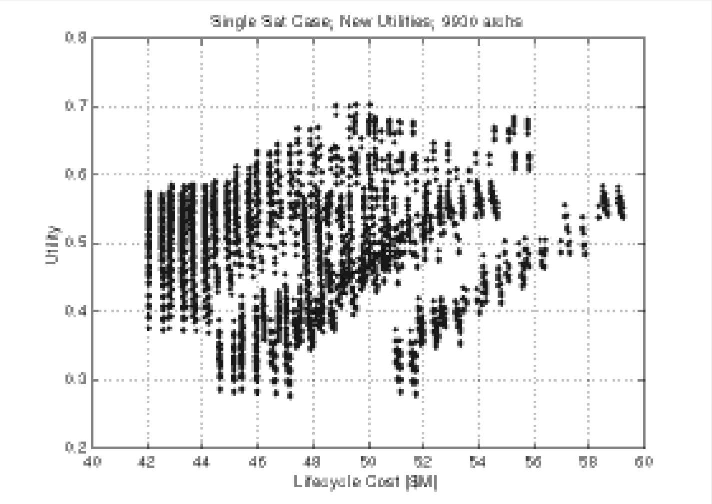
Point designs in a tradespace can be linked as a network via transition rules to assess changeability

Dynamic Multi-Attribute Tradespace Exploration Method

Implications for Systems Engineering Practice

1. Ability to explore many design options and prevent too early focus on single 'point design'
2. Enables quantitative assessment of factors such as variability in technical performance and cost, and impacts in markets
3. Suitable to multiple domains and demonstrated to improve design decision making

Vision: designers will have an enhanced ability to consider concept alternatives in a rigorous way, not only for present situation but also in considering futures where needs and contexts have shifted



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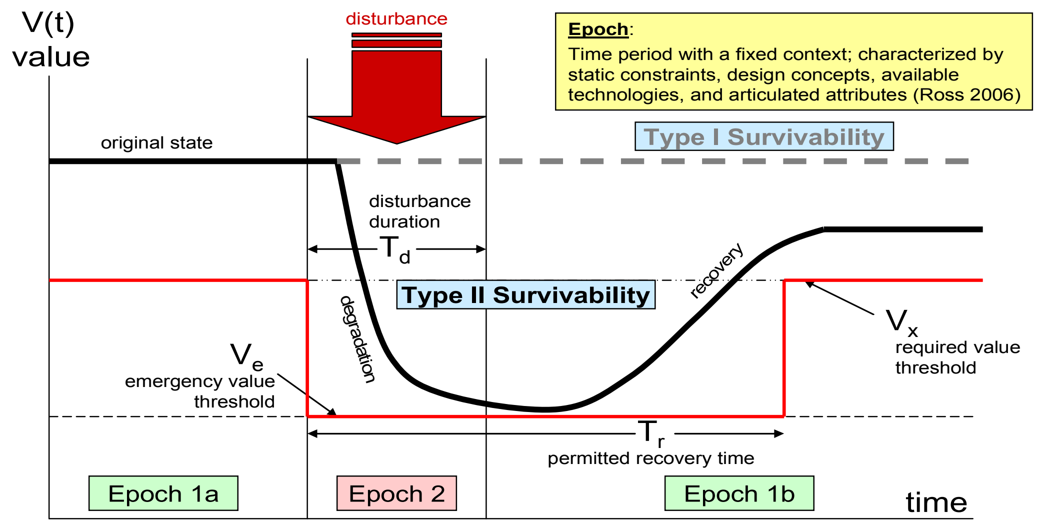
Architecting Principles for Survivable Systems

Research goal is to improve aerospace system survivability by informing future acquisitions using a dynamic tradespace exploration framework for analyzing, quantifying, and specifying survivability

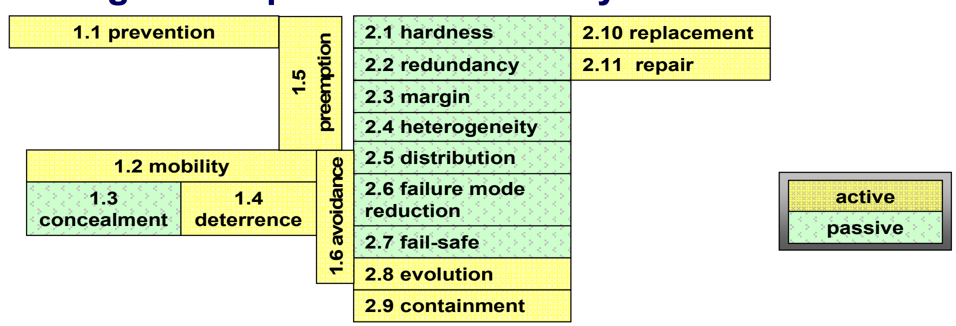
M.G. Richards, A.M. Ross, D.E. Hastings, and D.H. Rhodes, "Design Principles for Survivable System Architecture," 1st Annual IEEE Systems Conference, Honolulu, HI, April 2007

Definition of Survivability

Ability of a system to minimize the impact of a finite disturbance on value delivery through either (**I**) the reduction of the likelihood or magnitude of a disturbance or (**II**) the satisfaction of a minimally acceptable level of value delivery during and after a finite disturbance



Design Principles of Survivability



Architecting Principles for Survivable Systems -- Research Design

1. Knowledge Capture and Synthesis (descriptive)

literature review, exploratory interviews, exploratory case studies

system data
analysis techniques

existing theory
empirical data

2. Theory Development (normative)

- "ilities" framework
- Survivability conceptualization
- Tool box of design principles
- Dynamic tradespace metrics for passive and active survivability

internal validation

data

methods

3. Computer Experimentation (theory evaluation)

external validation

methods

data

4. Case Applications (prescriptive)

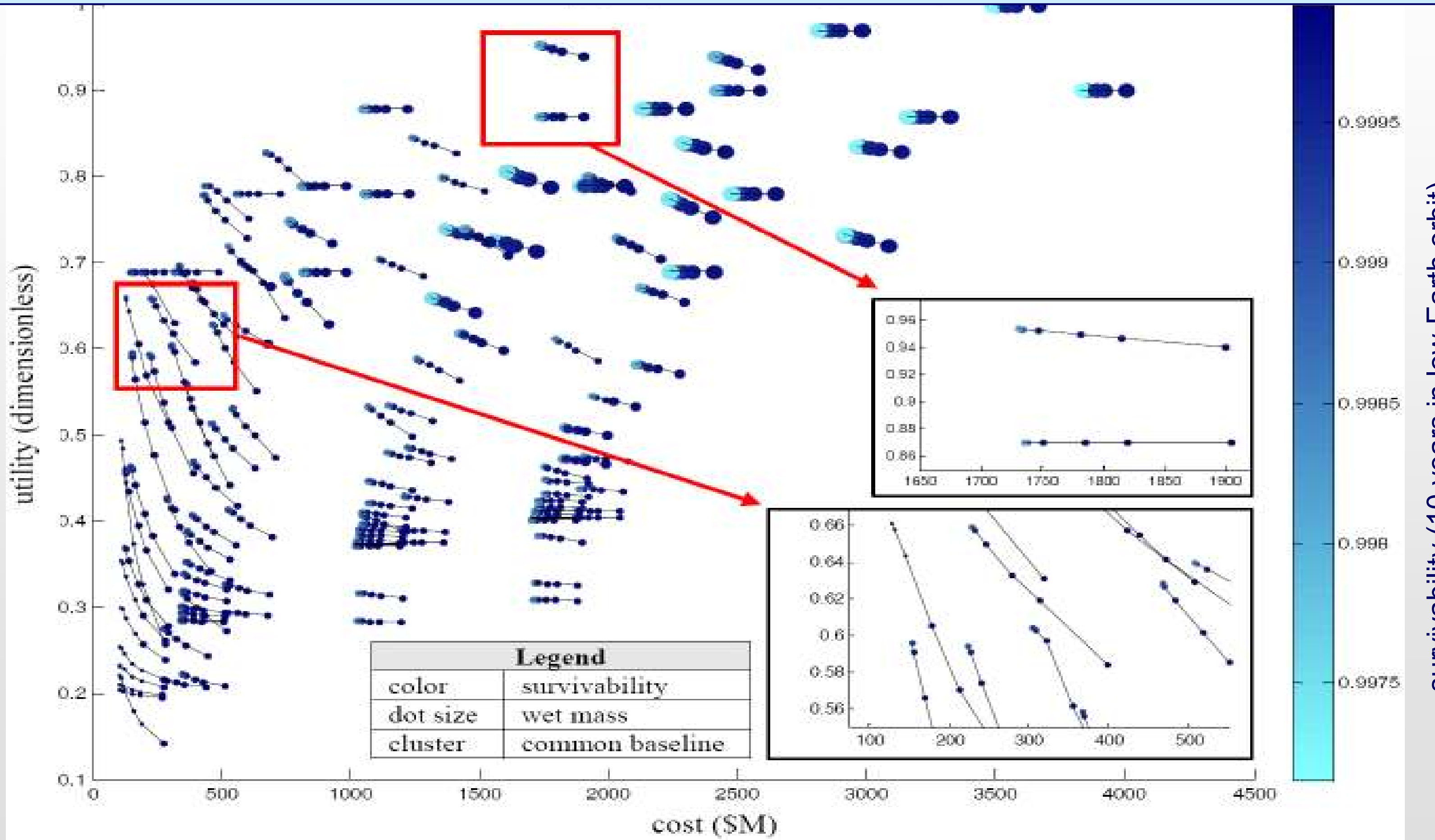
- Evaluation on real world cases

Matt Richards
MIT ESD Doctoral Candidate

- Iterative, concurrent process
- Employment of quantitative and qualitative research methods

Computer Experimentation: Preliminary Survivability Tradespaces

What is the impact of shielding on the survivability of space tug vehicles to orbital debris?



McManus, H., Richards, M., Ross, A., and Hastings, D., "A Framework for Incorporating "ilities" in Tradespace Studies," *AIAA Space 2007*, Long Beach, CA, September 2007.

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Dynamic Tradespace Exploration of Systems of Systems

System of systems engineering requires continuous tradespace exploration as constituent systems enter and exit the system

Research targeted at providing a more rigorous method for architectural decision making

Emerging design and analysis constructs can help identify and define SoS designs that are value robust to changes

- System shell
- Epoch-Era Analysis

D. Chattopadhyay, A.M. Ross and D.H. Rhodes, "A Framework for Tradespace Exploration of Systems of Systems," 6th Conference on Systems Engineering Research, Los Angeles, CA, April 2008

Assuming that an SoS can be designed ….

For SoS where the constituent systems and the interfaces can in some way be selected by an SoS designer – there is a need for a method to compare design alternatives in SoS to explore alternatives

Tradespace Exploration of Systems of Systems

SoS Issues in Tradespace Exploration

Stakeholder Analysis	•Different levels of **control** of SoS architect over constituent systems, results in potential complications in alignment of constituent systems •Value proposition must include **local and global value** at constituent and SoS level
Dynamic System Properties	•Constituent systems can join or leave – **time-varying design variable set** •Design for **stable, intermediate states** so that acceptable value is delivered when SoS changes due to change in constituents
Legacy and New Constituent Systems	•Existing or legacy systems have **constrained design** and operational environment; new constituent systems do not – design space is complicated •If constrained by legacy constituents, may need to concentrate on **designing the interfaces** between constituents

Chattopadhyay, D., Ross, A.M., and Rhodes, D.H., "A Framework for Tradespace Exploration of Systems of Systems," 6th Conference on Systems Engineering Research, Los Angeles, CA, April 2008.

Future Research Directions

1. Application of dynamic tradespace exploration method to several domains leading to domain-neural validation
2. Further characterization of architecture approaches for enhancing changeability
3. Further research on Epoch-Era Analysis, providing for visualization and structured way to make decisions in the temporal value environment

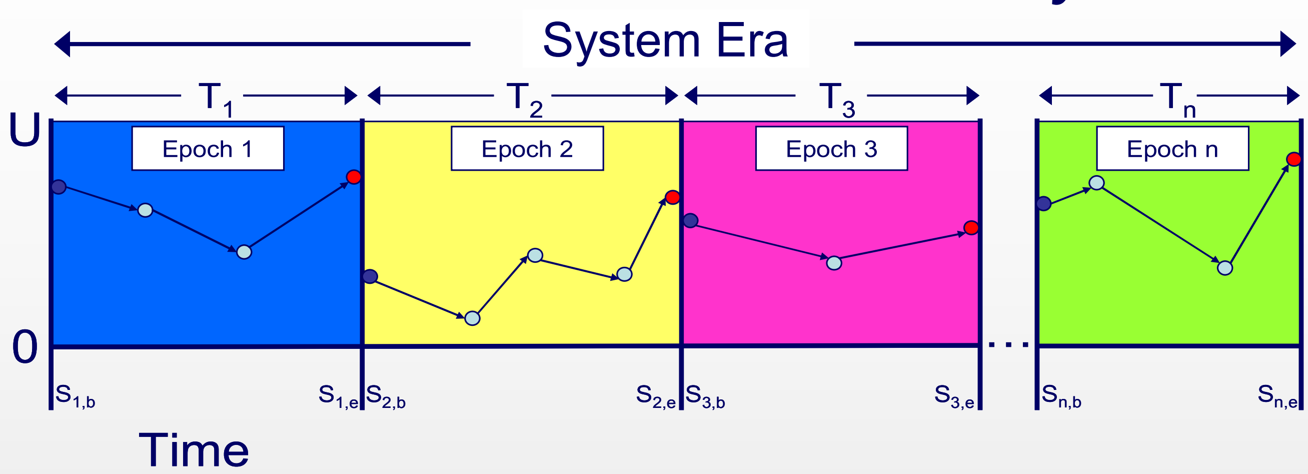
J. Nickel, A.M. Ross, and D.H. Rhodes, Cross Domain Comparison of Design Factors in System Design and Analysis of Space and Transportation Systems, 6th Conference on Systems Engineering Research, April 2008

A.M. Ross and D.E. Hastings, "Assessing Changeability in Aerospace Systems Architecting and Design Using Dynamic Multi-Attribute Tradespace Exploration," AIAA Space 2006, San Jose, CA, Sep 2006

A.M Ross and D.H. Rhodes, "Using Natural Value-Centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis" SEAri Working Paper, WP-2007-1-3, 2007, http://seari.mit.edu, INCOSE International Symposium 2008, Utrecht, The Netherlands, June 2008

Epoch-Era Analysis

natural value-centric life cycle

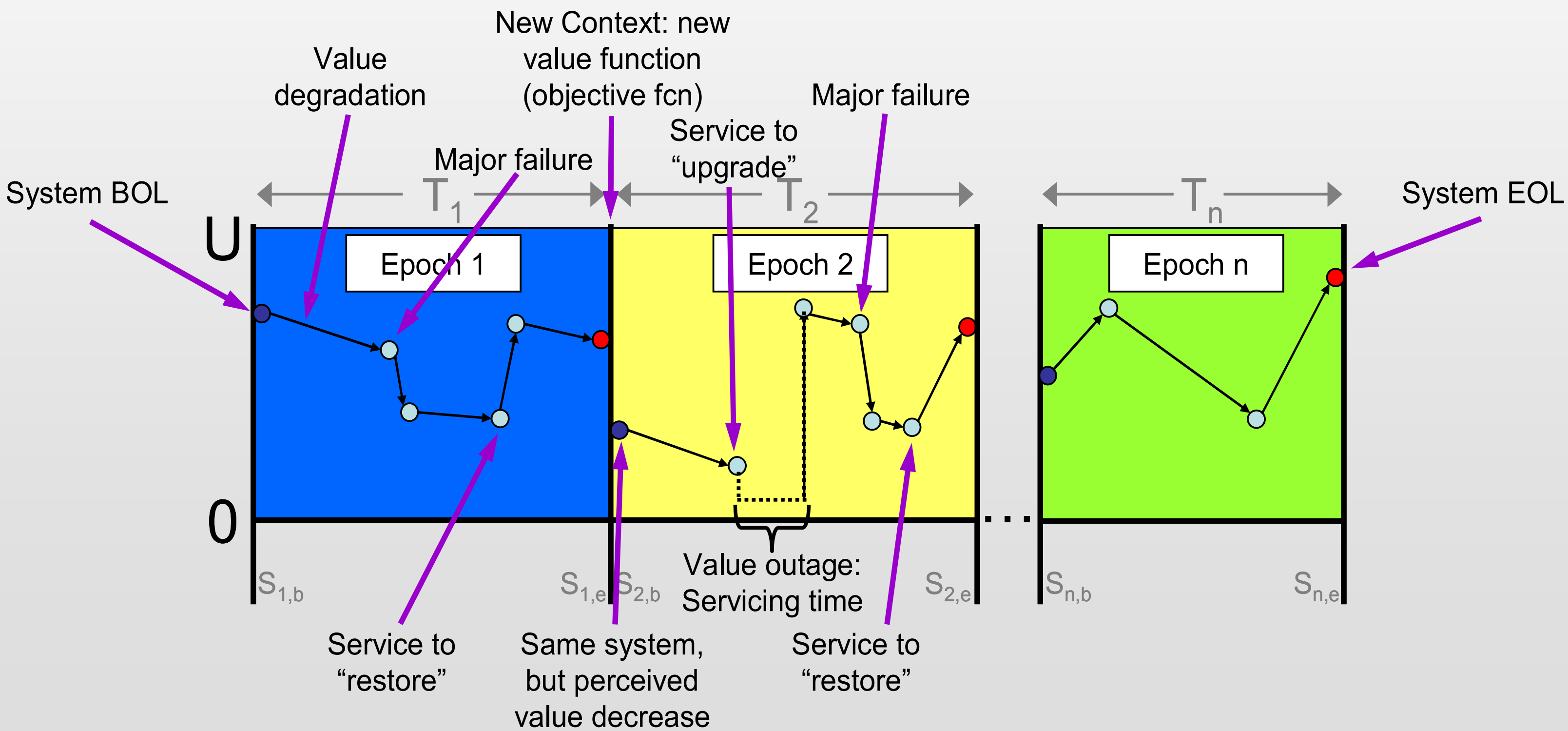


- Epoch is a time period for which context and expectations are fixed
- Multi-attribute utility functions, constraints, design concepts, available technologies, and articulated attributes are defined for an Epoch
- Epoch bounds the change scenario – when change occurs, a new Epoch is defined
- Epochs are strung together to form the system era

Example
Satellite with Serviceability

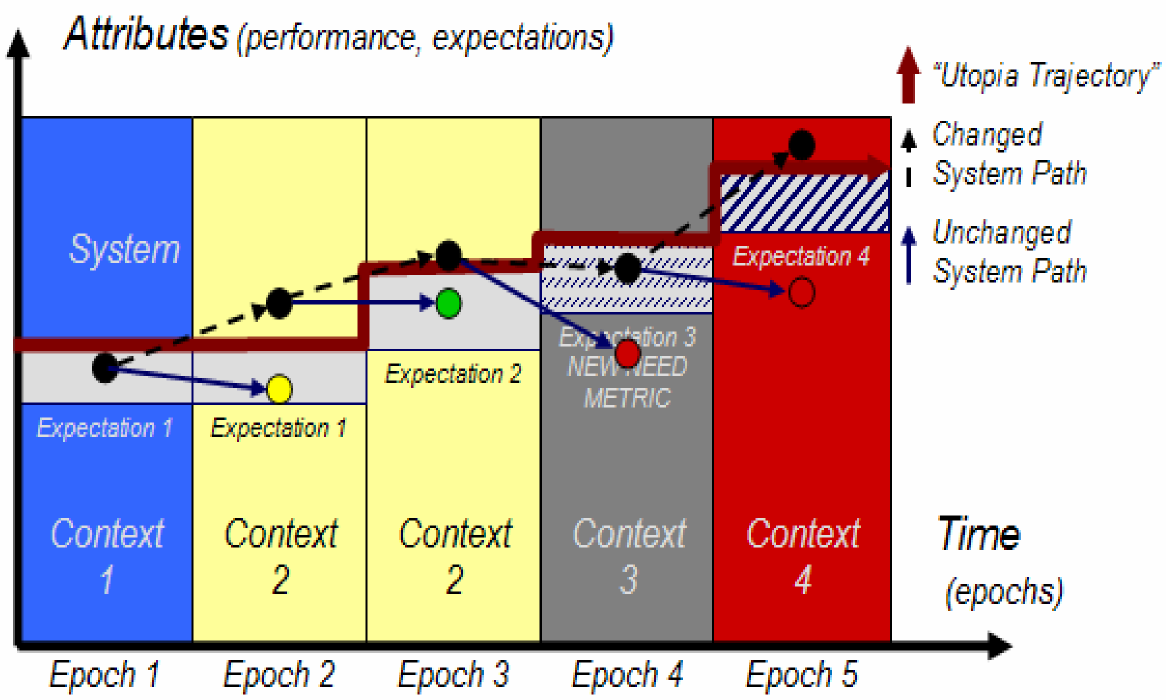
Epoch-Era Analysis considers changes in (1) user needs and expectations, (2) context (or environment in a broad sense), and (3) the product itself.

Epoch-Era Analysis allows for discretization of the future product timeline into a series of short run *Epochs* of fixed *Expectations* and *Context*,



Epoch-Era Analysis

- **Each epoch has fixed context and expectations**
- **Value of the system may degrade in a new epoch; changing the system may restore value**
- **Utopia trajectory is optimal value delivery at least cost across epochs**



Epoch-Era Analysis for Evaluating System Timelines in Uncertain Futures

Objective

- Apply Epoch-Era Analysis to large space system of a US Government Agency

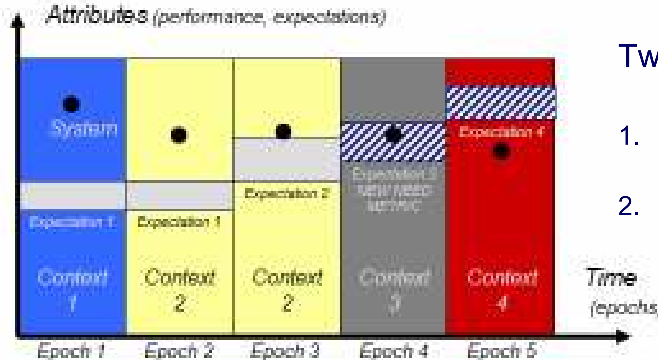
Method

- Enumerate future needs and contexts (incl. technology, policy, etc.)
- Develop models
- Run simulations

Anticipated Contributions

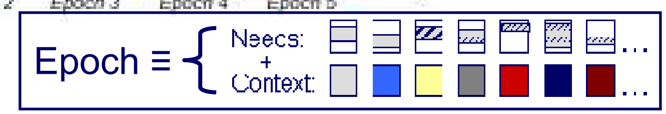
- Validate dynamic analysis technique for evaluating system performance under large number of future contexts and needs
- Develop metric for representing dynamic system success across changing futures: "*utopia trajectory*"

Changing Futures Impact on System

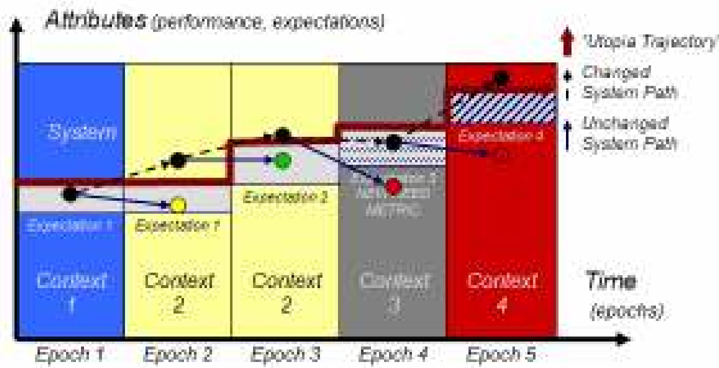


Two aspects to an ***Epoch***:

1. Needs (expectations)
2. Context (constraints, etc.)



Dynamic Strategies for Systems



Dr. Adam M. Ross and Dr. Donna H. Rhodes– Government Agency Sponsored Project

Sponsor Engagement Models

Classical "basic research" sponsors
- Fundamental theory development

Innovation grant sponsors
- Discovering extensions of foundational research

Contract research sponsors
- Applying VR research to sponsor problem

Consortium sponsors
- Developing a generalized VR method

"Deep engagement" partnerships

Research Engagement Model
"Deep Engagement"

Value robustness research involves many stakeholders and necessitates understanding real world system contexts

Use of deep engagement model

- Validate and enhance methods
- "Tune" methods to sponsor environment
- Contribute to growth in sponsor's capabilities
- Enhance researcher's understanding of practice

MIT *SDM Pulse*

March 2008

A key factor in this type of collaboration is "connecting like-minded people in both organizations, where our methodology development research is linked to a problem the sponsor views as strategically important."

Transition to Practice

Education	Access to Research
http://professionalinstitute.mit.edu	**http://seari.mit.edu**

MIT Professional Institute

Value-Driven Tradespace Exploration for System Design

D. Rhodes, A. Ross, H. McManus

June 9-12, 2008

MIT Campus | Cambridge, MA

Summary

- Contemporary environment and large-scale systems challenges motivate research in support of a new paradigm: *value robustness*
- Research aims to improve development of real world systems and systems of systems
- Multiple methods for sponsor engagement
  – Deep engagement with government and industry stakeholders in both research conduct and transition to practice is necessary