Systems Engineering Research in the Engineering Systems Context:

Value-Driven Architecting and Design of Engineering Systems

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Topics

PART I. Systems Engineering Research in the Engineering Systems Context

- Brief Overview of Engineering Systems and MIT Engineering Systems Division
- Comparison of Systems Engineering and Engineering Systems
- Impact of Engineering Systems on Systems Engineering and as a "Context Field" for Research
- MIT Systems Engineering Research within ESD – overview of research portfolio

Part II. Value-Driven Architecting and Design Research

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MIT Engineering Systems Division Academic Unit for SEAri

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

MIT's Engineering Systems Division (ESD) is a cross-cutting academic unit -- engineering, management, and social sciences.

It broadens engineering practice to include context of challenges as well as consequences of technological advancement

>50 faculty **>300 masters students** **>60 PhD students**

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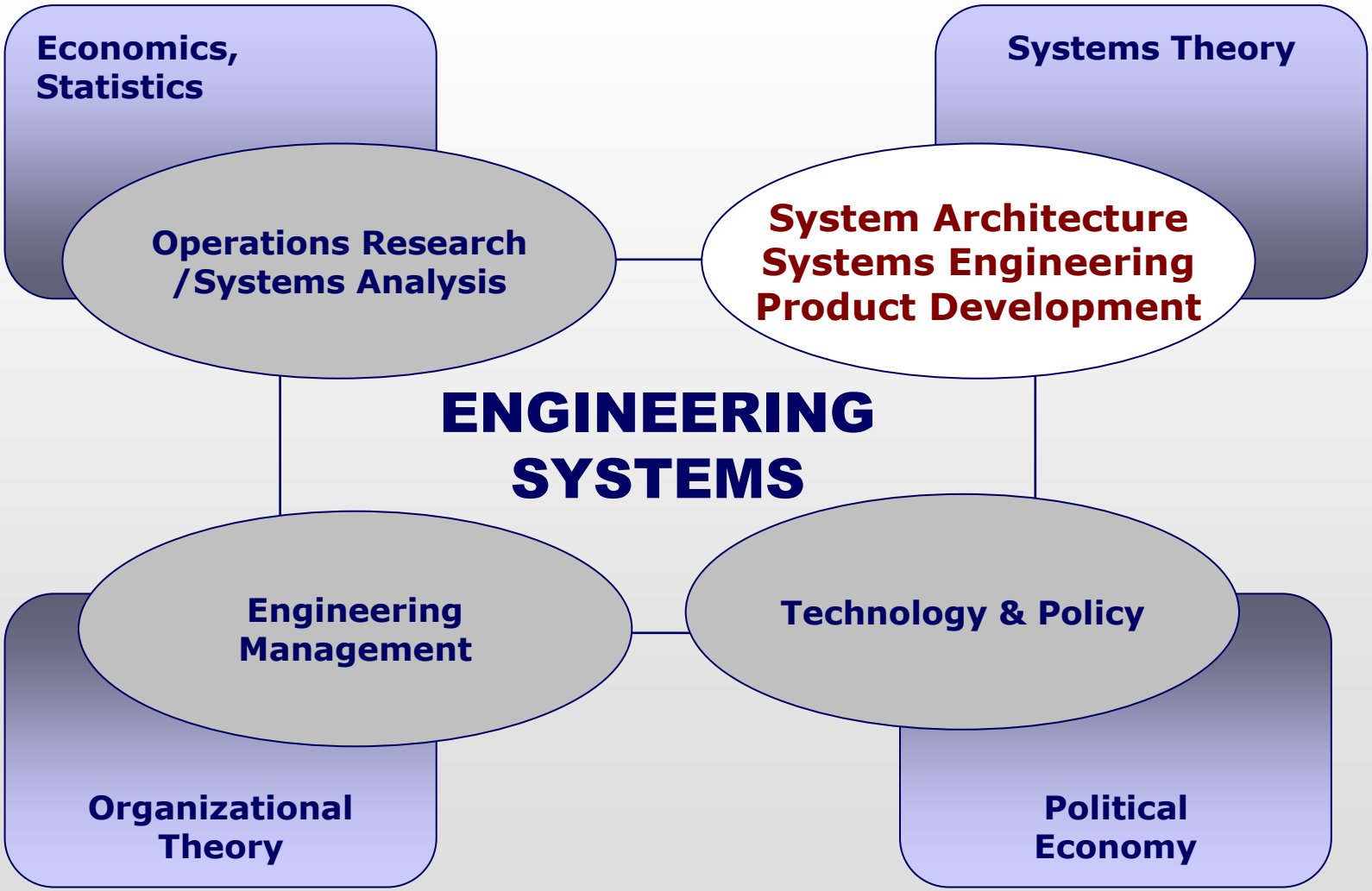
Engineering Systems as a Field of Scholarship



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Engineering Systems -- Important Perspectives

- A very **broad interdisciplinary perspective**, embracing technology, policy, management science, and social science.
- An **intensified incorporation of system properties** (such as sustainability, safety and flexibility) in the design process.
- **Enterprise perspective**, focusing on interconnectedness of product system with enterprise system that develops and sustains it.
- A **complex synthesis of stakeholder perspectives**, of which there may be conflicting and competing needs to be resolved to serve the highest order system need.

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Impact of Engineering Systems on Systems Engineering

personal perspective

ES provides a broader academic field of study (context field) for SE

ES has been a catalyst for universities coming together around a broader systems education agenda

ES brings together a more diverse set of researchers and scholars who can benefit from (and contribute to) systems engineering principles and research

ES establishes a larger footprint in an university to drive a strong research focus and investment in systems research

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MIT Engineering Systems Division Doctoral Program

Context: The Engineering Systems Division (ESD) at MIT is helping to pioneer Engineering Systems as a new field of study – designed to transform engineering education and practice.

Mission: The ESD doctoral research programs conduct original and generalizable scholarship on complex engineered systems in order to advance theory, policy, or practice. Main objective of the program is to prepare colleagues who can seed engineering schools with the integrative ideas of engineering systems.

Transforming engineering education, research, and practice through the emerging field of engineering systems

Preparing engineers to think systemically, lead strategically, and address the complex challenges of today's world, for the benefit of humankind

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MIT ESD Doctoral Program

ESD Doctoral Seminar

Quantitative Methods

Social Science Research Methods

Courses in:

- **Systems Theory -- to design or refine a system**
- **Systems Policy -- to influence or direct a system**
- **Systems Evaluation -- to evaluate / analyze / characterize a system**

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Sample of ESD Doctoral Theses

- ***The Duality of Innovation: Implications for the Role of the University in Economic Development***
- ***A Life-Cycle Flexibility Framework for Designing, Evaluating, and Managing "Complex" Real Options: Case Studies in Urban Transportation and Aircraft Systems***
- ***Stakeholder-Assisted Modeling and Policy Design Process for Engineering Systems***
- ***Shaping the Terms of Competition: Environmental Regulation and Corporate Strategies to Reduce Diesel Vehicle Emissions***
- ***Architectural Innovation, Functional Emergence and Diversification in Engineering Systems***
- ***Managing Unarticulated Value: Changeability in Multi-Attribute Tradespace Exploration***
- ***Climate Policy Design: Interactions among Carbon Dioxide, Methane, and Urban Air Pollution Constraints***
- ***Symbiotic Strategies in Enterprise Ecology: Modeling Commercial Aviation as an Enterprise of Enterprises***
- ***System Architecture Analysis and Selection Under Uncertainty***
- ***Corporate Decision Analysis: An Engineering Approach***
- ***Real Options "in" Projects and Systems Design – Identification of Options and Solution for Path Dependency***
- ***Effective Information Integration and Reutilization: Solutions to Technological Deficiency and Legal Uncertainty***

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Comparison of Systems Engineering and Engineering Systems

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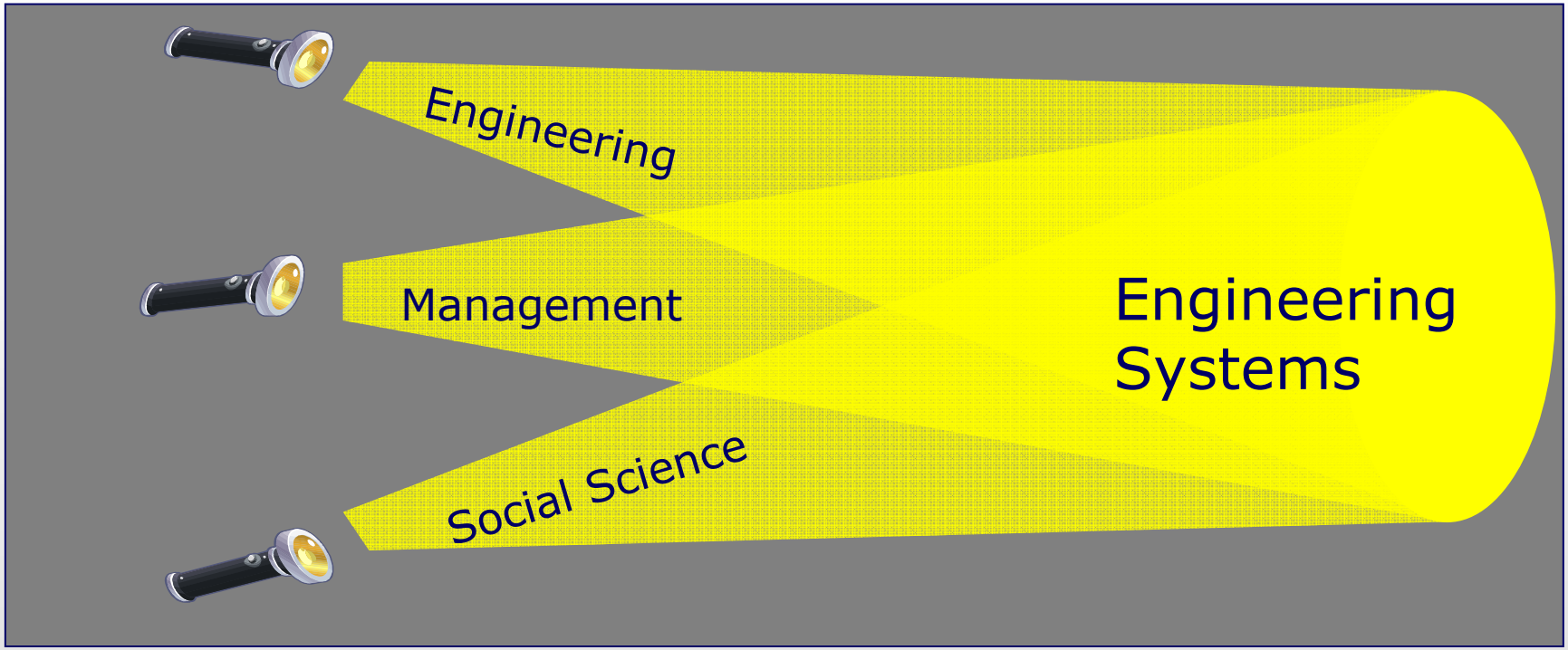
Engineering Systems: Field of Scholarship



ENGINEERING SYSTEMS

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.

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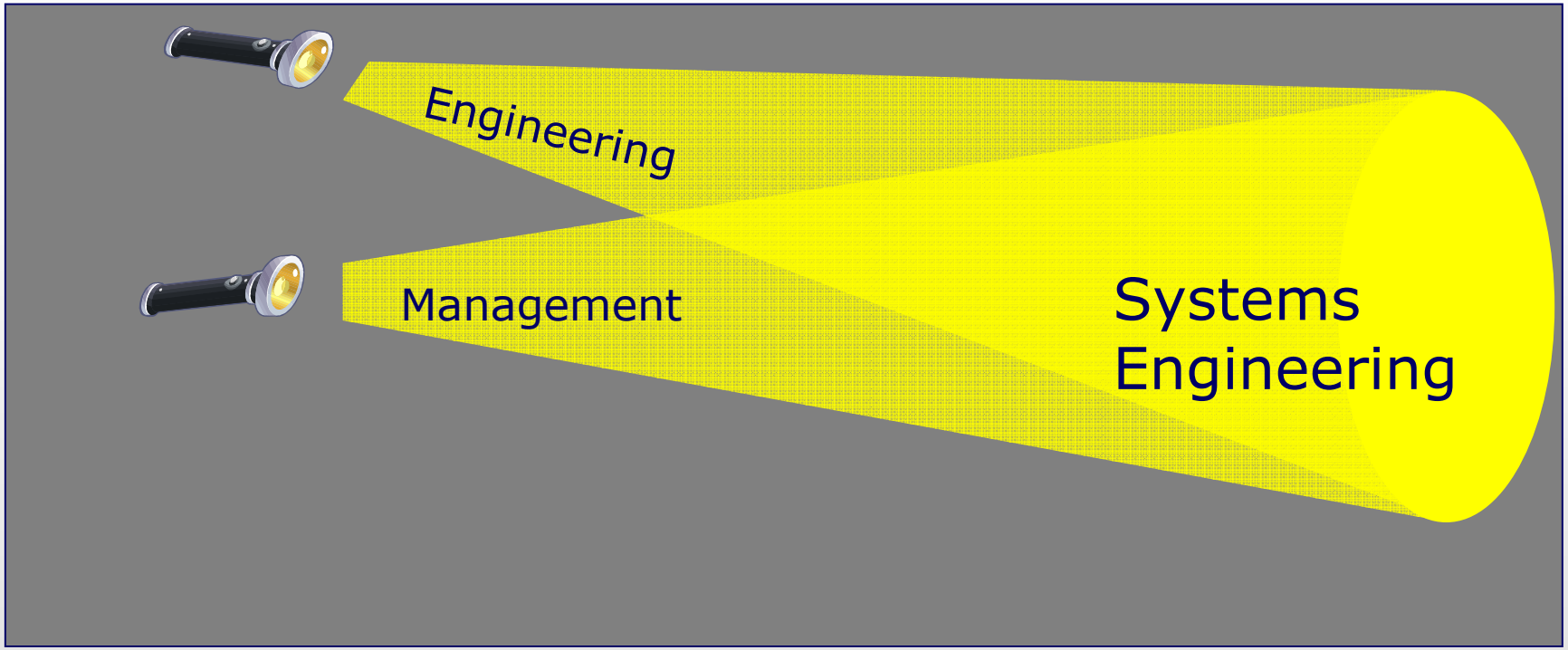
Systems Engineering
Field of Practice



Systems Engineering

Considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.

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SE versus ES
What Is the Difference?

SYSTEMS ENGINEERING (Traditional)

Systems engineering is the **process** of selecting and synthesizing the application of the appropriate scientific and technical knowledge in order to translate system requirements into system design. (Chase)

SYSTEMS ENGINEERING (Advanced)

Systems engineering is **a branch of engineering** that concentrates on design and application of the whole as distinct from the parts… looking at the problem in its entirety, taking into account all the facets and variables and relating the social to the technical aspects. (Ramo)

ENGINEERING SYSTEMS

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.

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Unique Perspectives

	Systems Engineering	*Engineering Systems*
Scope	**Small to large scale subsystems, systems, system of systems**	**Large-scale, complex open systems that are technologically enabled**
Focus	**Primary focus is on product/service system**	**Holistic attention to product/service system and larger enterprise system**
Policy	**Viewed as fixed and constraining system solution**	**Viewed as variables --can be created or adapted for overall solution**
Socio-technical	**Viewed as considerations in engineering**	**Viewed as primary in an overall system solution**
Primary Stakeholders	**Primary focus on customer and end-users with secondary focus on other stakeholders**	**Balanced focus on all stakeholders impacted by engineering system -- product, enterprise, environment**
Roles	**System architects, systems engineers, related specialists performing systems engineering process**	**System architects, enterprise architects, engineers, operations analysts, project managers, policy makers, social scientists, and others**

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Essential Points

1. Engineering Systems is **not renaming or replacing** Systems Engineering!
   - Confusion arises as some think MIT just re-ordered the two words “systems” and “engineering”
2. Engineering Systems is a **field of academic study** – not a practice, profession, or process.
3. Engineering Systems is **not equivalent in scope** to Systems Engineering
4. Evolving the field of ES can have a **positive impact on evolving** SE – as a field and practice

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SEARI
Systems Engineering Advancement Research Initiative

Impact of Engineering Systems on Evolving Systems Engineering?

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SEARI
Systems Engineering Advancement Research Initiative

Classical systems engineering principles and practices need to be adapted and expanded to fully support engineering of highly complex systems

What SE principles and practices are too limited at present to effectively deal with large-scale socio-technical systems?

How can these be adapted and expanded with contributions from of the field of Engineering Systems?

What lifecycles, practices and methods, when harmonized or adapted, can result in an emergent approach that can better serve the needs of the entire engineering system (technological system and enterprise)?

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SEA RI
Systems Engineering Advancement Research Initiative

ES and SE are both evolving fields… it is critical that they evolve synergistically and not as decoupled fields

How can the varied definitions and views of Systems Engineering converge within the context of Engineering Systems?

Is there a common taxonomy that will serve the needs of Engineering Systems and Systems Engineering?

What other sub-fields of Engineering Systems are highly interrelated to Systems Engineering, and what research is needed to explore convergence or cooperation of these sub-fields?

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SEA RI
Systems Engineering Advancement Research Initiative

For ES to become the context field for SE, there must be changes in systems education strategies, policies, structures

Can ES provide the context field for SE which has never quite fit as engineering science or management science?

How will universities need to evolve their structures and policies?

How will existing Systems Engineering curricula need to change?

What strategies can be used to transition current educational models to this new model?

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Engineering Systems Research Landscape

an intellectual environment for systems research

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

1. **Provides context for research agenda, methods, and 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

Multi-disciplinary focus– engineering, management, social sciences
Draws from both quantitative and qualitative approaches
Deep engagement with real world industry and government projects

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Advancing SE using ES

Engineering Systems provides the "research landscape" context for advancing traditional systems engineering

Using *Engineering Systems*, research advances the methods and tools for *Systems Engineering* practice

Engineering Systems Methods/Tools

E.g. "Social science methods", technology policy, etc.

Systems Engineering Methods/Tools

E.g. "Engineering methods", numerical approaches, etc.

Engineering Systems scope includes more than Systems Engineering

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Systems Engineering Research within MIT Engineering Systems Division

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Systems Engineering Advancement Research Initiative within MIT ESD

MIT SEAri Mission

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

Considerations:

1. **Mental model and strategic focus**
2. **Underlying structure for research**
3. **Core methods and theoretical base**
4. **Research Portfolio – organizing projects**
5. **Sponsor engagement models**
6. **Sharing research knowledge**
7. **Transitioning research to practice**

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**

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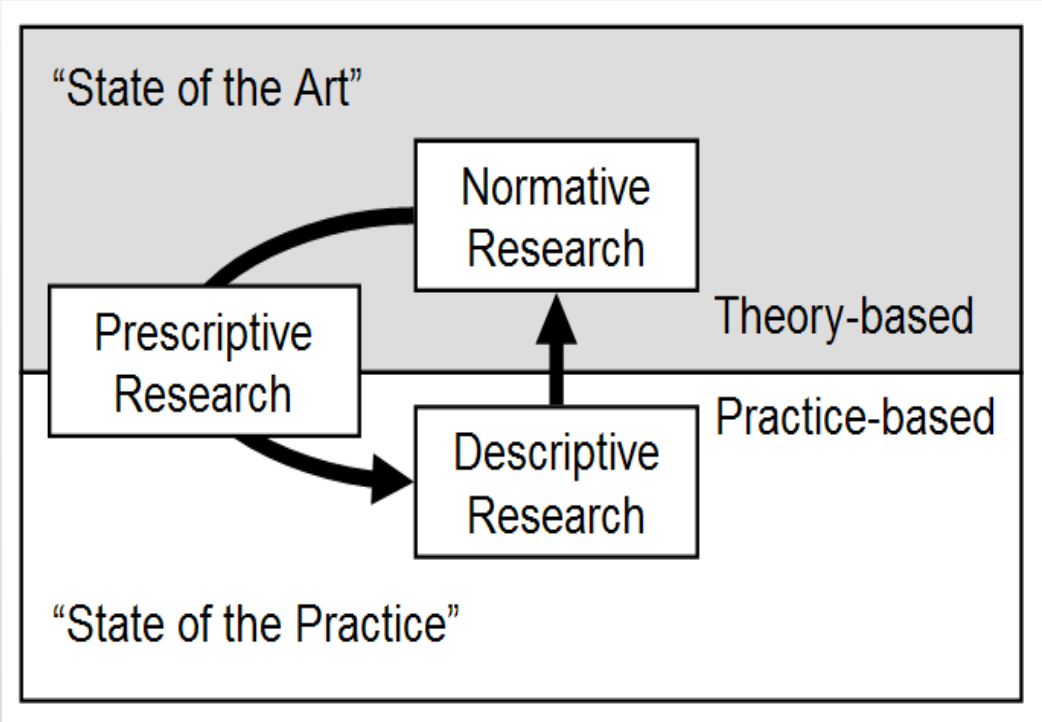
SEAri Underlying Research Structure

Prescriptive methods seek to advance state of the 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**

Qualitative and quantitative methods



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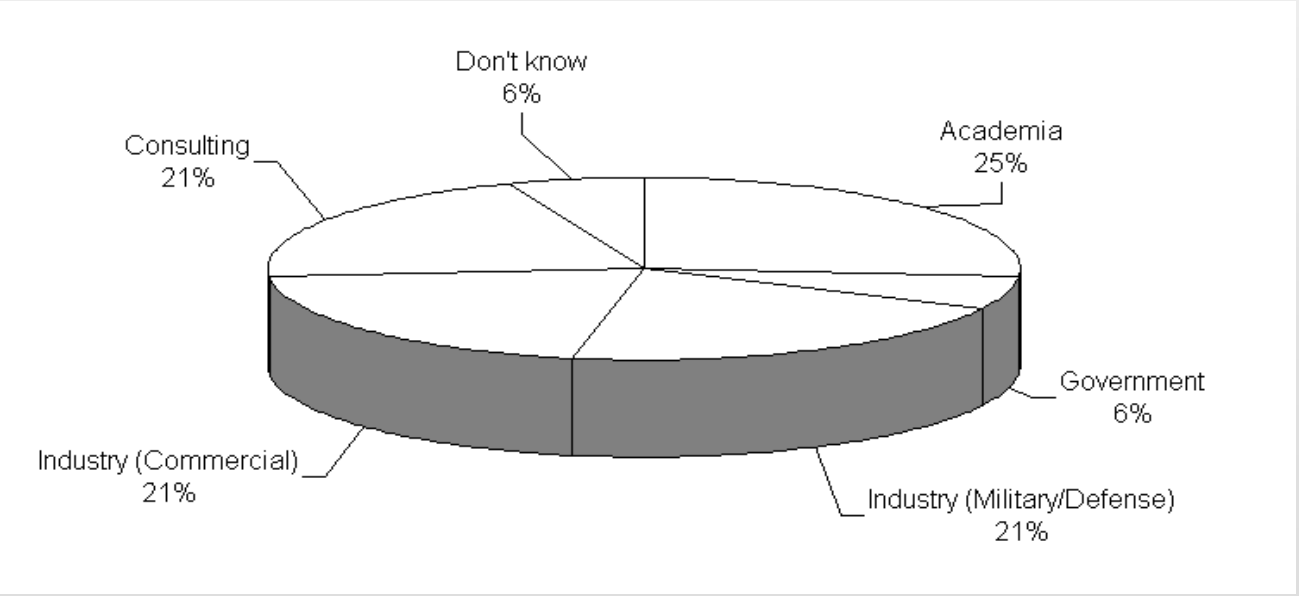
Research Predisposed Toward Application

For most engineering students, the goal of a career in industry motives their pursuit of advanced study and this will increasingly be the case on the future. Because of this, engineering students' outlook on research is predisposed toward application in engineering practice

National Academy of Engineering, 2005

Survey of SEANET doctoral students shows only 25% plan academic careers



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Sponsor Engagement Models

Classical “basic research” sponsors
- Targeted topic toward broad scientific goals

Innovation grant sponsors
- Higher risk/higher payoff research

Contract research sponsors
- Toward solving sponsor problem

SE Research requires real world laboratory

Consortium sponsors
- Pooled funds for shared research benefits

“Deep engagement” partnerships
- Symbiotic relationship

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Examples of Research

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Engineering Systems -- Important Perspectives

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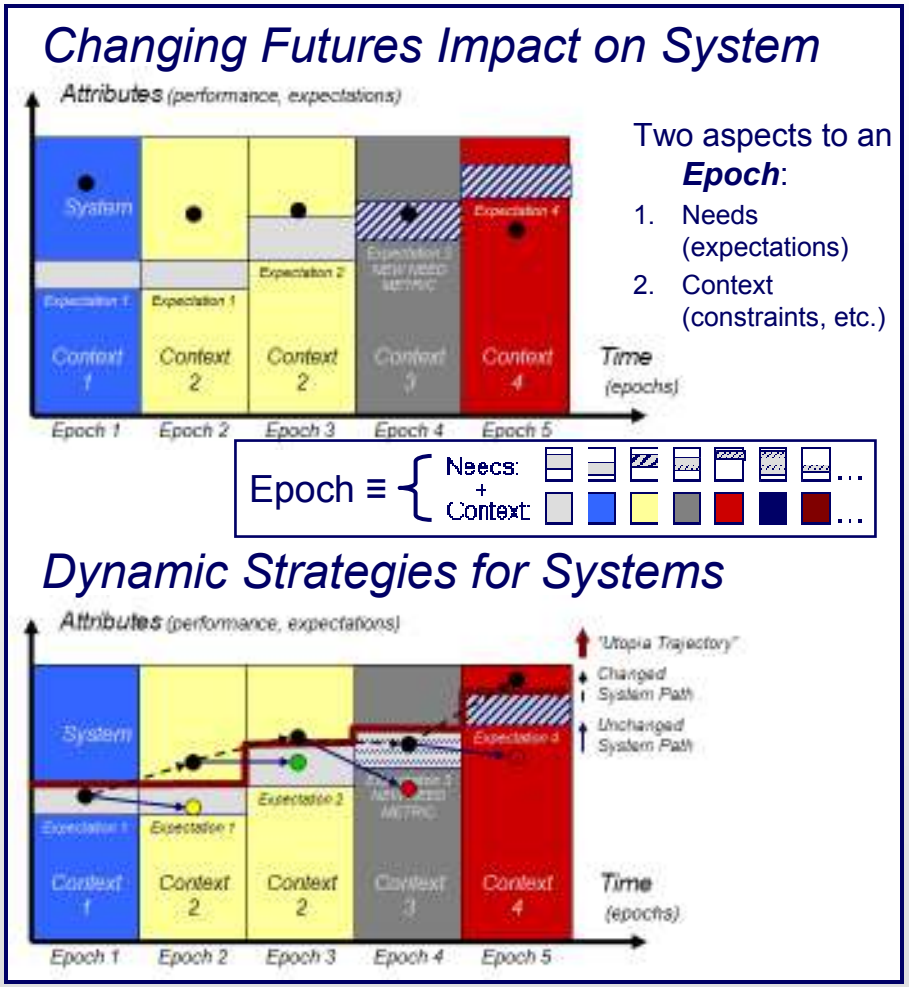
Epoch-Era Analysis for Evaluating System Timelines in Uncertain Futures

- Dynamic analysis technique for evaluating system performance under large number of future contexts and needs
- Draws from theories and approaches from multiple disciplines
- Involves the enumeration of future needs and contexts including technology, policy, social and environmental factors, and others



Ross and Rhodes, 2008

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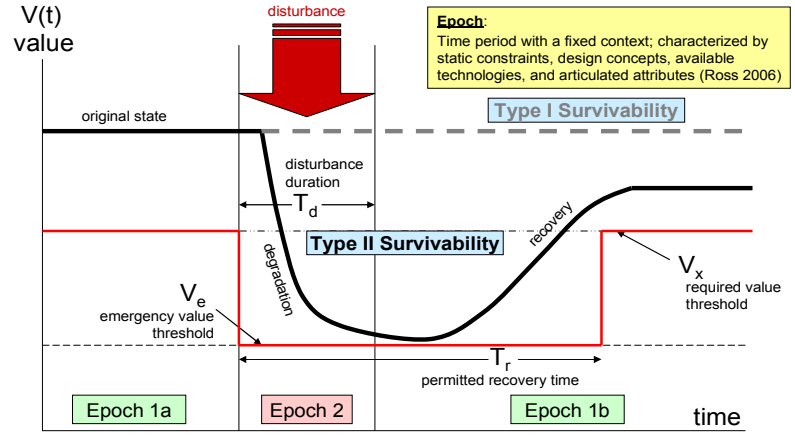
Architecting for Survivability

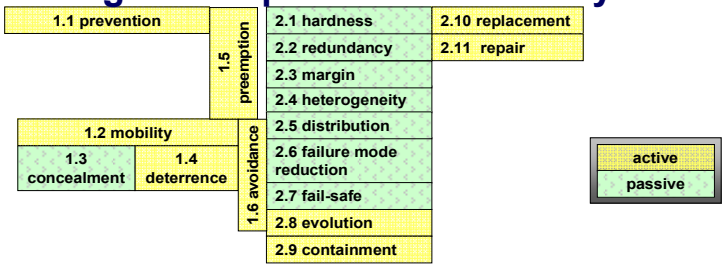
- **Dynamic, value-centric conceptualization of survivability**
- **Set of general design principles for survivability**
- **Empirically validated**
- **Extensions of dynamic tradespace exploration to accommodate hostile and natural disturbances**

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



Richards, et al 2008

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Collaborative Distributed Systems Engineering

- Empirical case studies to identify successful practices and lessons learned when SE teams collaborate across geographic locations
- Enterprise social and technical factors studied: collaboration scenarios, tools, knowledge and decision management, culture, motivations, others
- Successful development of the technical product dependent upon socio-technical factors in the enterprise

<u>Success Factor</u>: Invest in Up-front Planning Activities

Spending more time on the front- end activities and gaining team consensus shortens the implementation cycle. It avoids pitfalls as related to team mistrust, conflict, and mistakes that surface during implementation.

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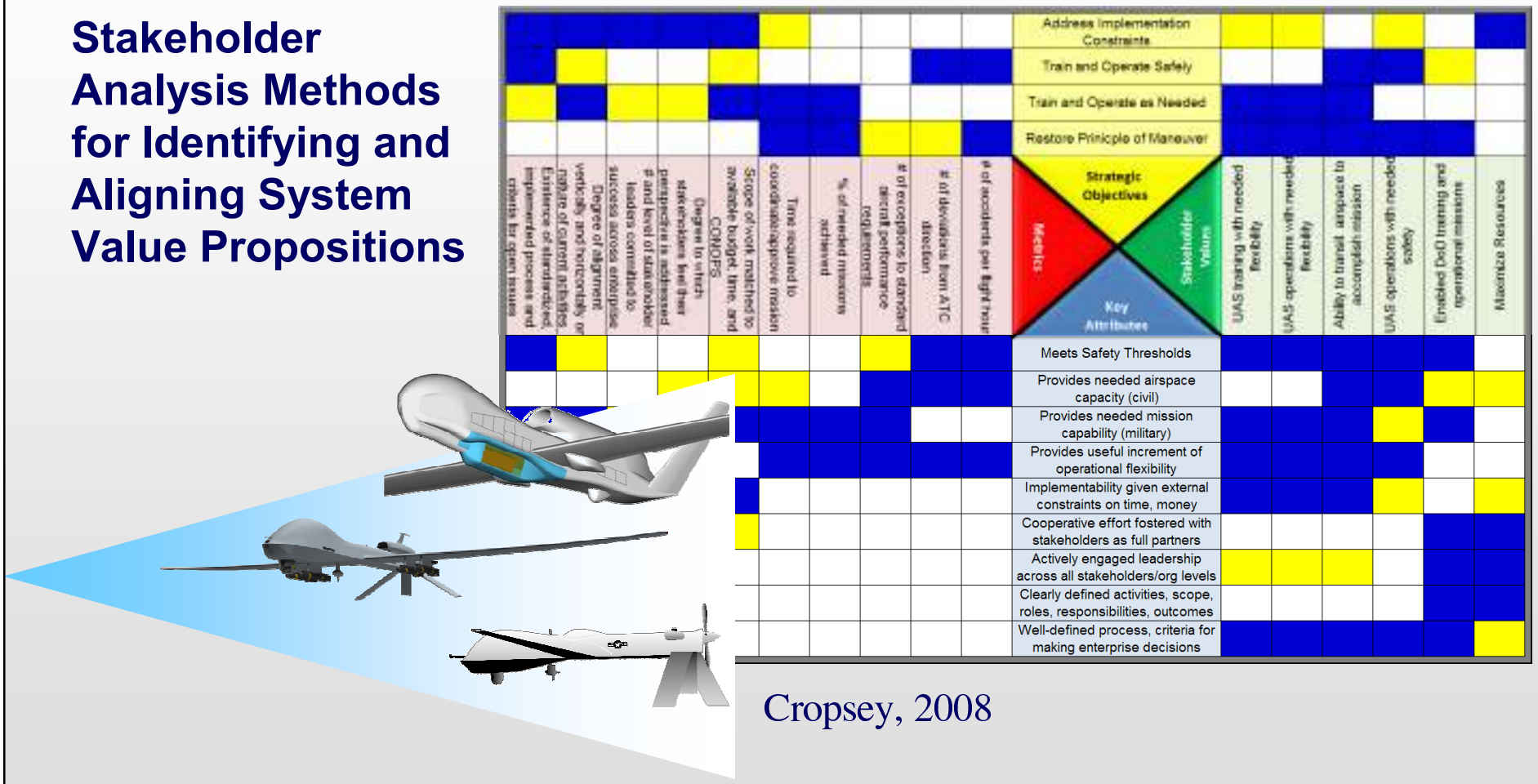
Stakeholder Alignment

Stakeholder Analysis Methods for Identifying and Aligning System Value Propositions



Cropsey, 2008

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Part II. Value-Driven Architecting and Design Research

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SEAri Research Portfolio

RESEARCH PORTFOLIO TOPICS

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

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Research Portfolio (1)

SOCIO-TECHNICAL DECISION MAKING

This research area seeks to develop multi-disciplinary representations, analysis methods, and techniques for improving decision making for socio-technical systems. Examples include:

- Studies of decision processes and effectiveness of techniques
- Constructs for representing socio-technical systems for impact analysis on costs, benefits, and uncertainties
- Effective visualization of complex tradespaces
- Understanding and mitigating cognitive biases in decision processes
- Developing dynamic system strategies (e.g. timing technology investments and execution of system change options)
- Methods for representing distribution of costs and benefits to multiple stakeholders of socio-technical systems

Representations, analysis methods, and techniques for improving socio-technical decision making

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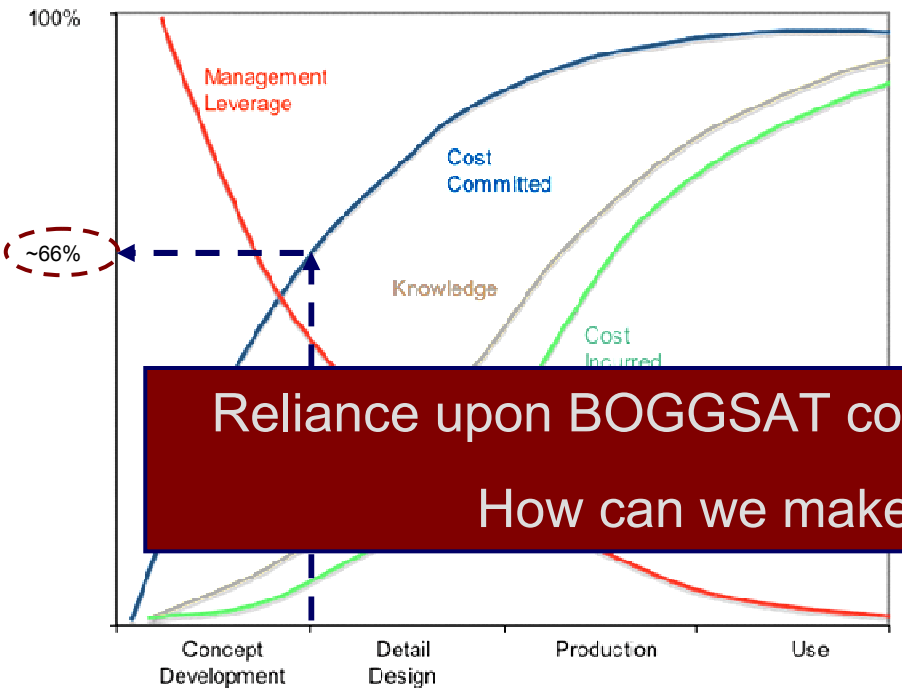
The Scope of Upfront Decisions

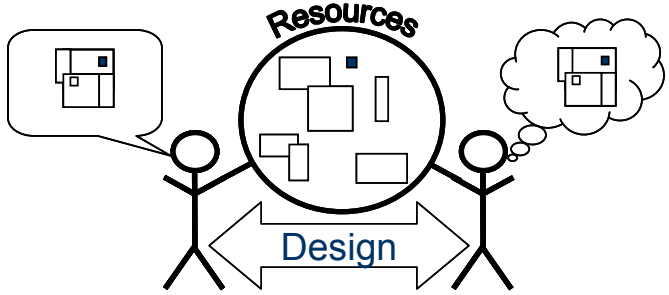
Conceptual Design is a high leverage phase in system development



After Fabrycky and Blanchard 1991

Key Phase Activities

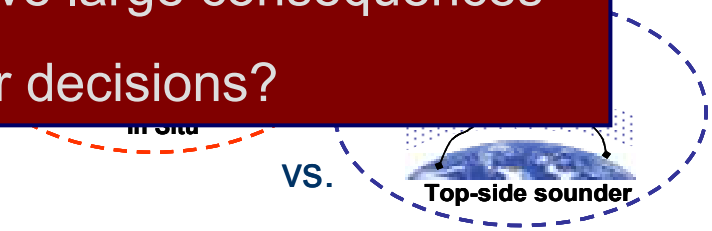
Needs Captured



Resources Scoped

Reliance upon BOGGSAT could have large consequences

How can we make better decisions?



Concept(s) Selected

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Three keys to good upfront decisions

- Structured program selection process
  - Choosing the programs that are right for the organization's stakeholders
- Classical systems engineering
  - Determining stakeholder needs, generating concept of operations, and deriving requirements
- Conceptual design practices
  - Finding the right form to maximize stakeholder value over the product (or product family) lifetime

"Good" system decisions *must* include both "socio" as well as "technical" components

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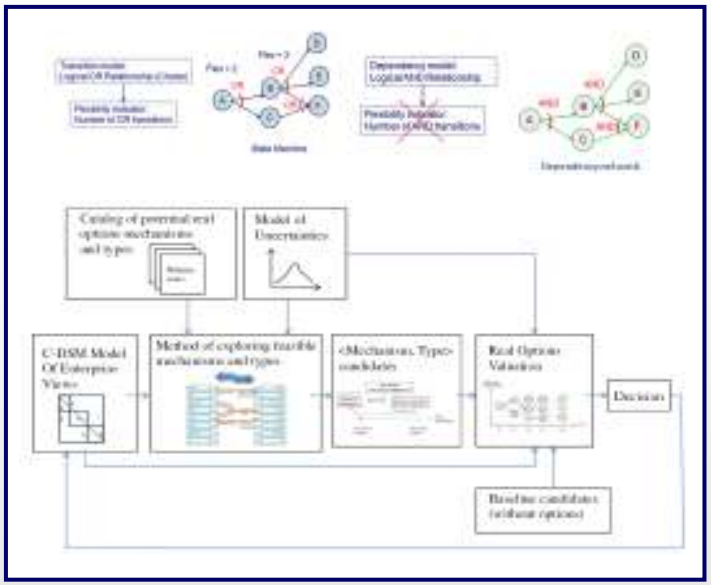
Flexibility Representations

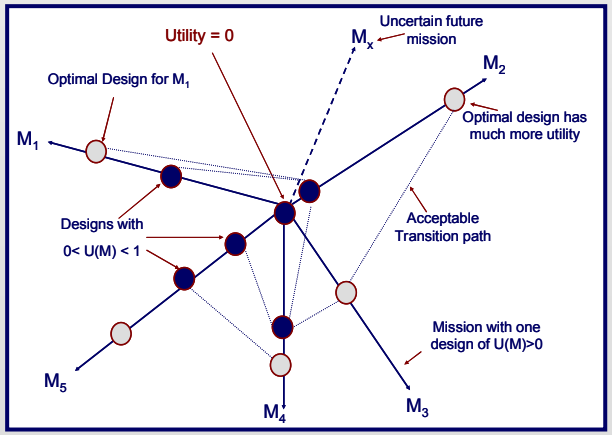


Managing Uncertainty in Socio-Technical Enterprises using a Real Options Framework

Tsoline Mikaelian, Aero/Astro PhD 2009

What enterprise representation/models can be used to identify potential real option investment opportunities?

How can real options be used for holistic decision making and architecting of socio-technical enterprises under uncertainty?



Metrics for Flexibility in the Operationally Responsive Space Paradigm

Lauren Viscito, Aero/Astro SM 2009

Can a flexibility metric be used for explicit trades in conceptual space system design?

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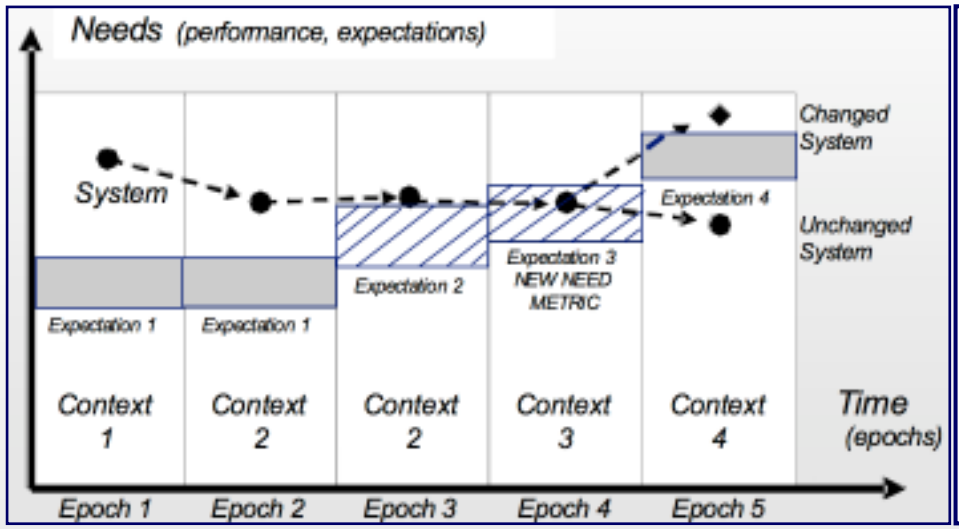
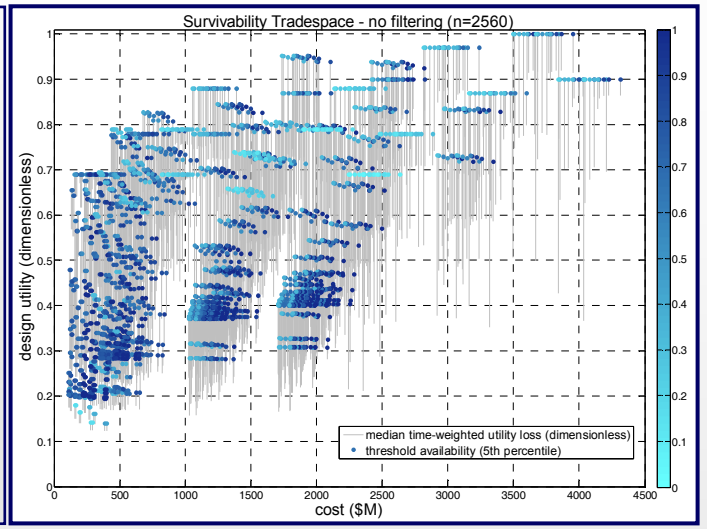
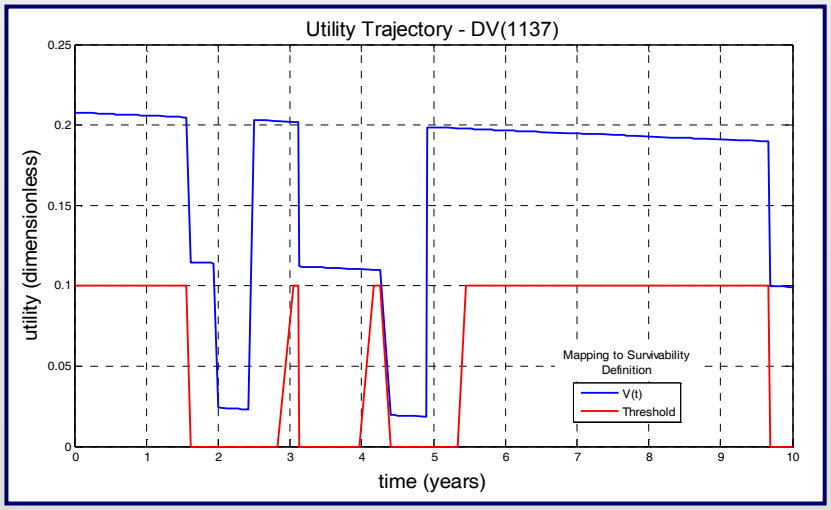
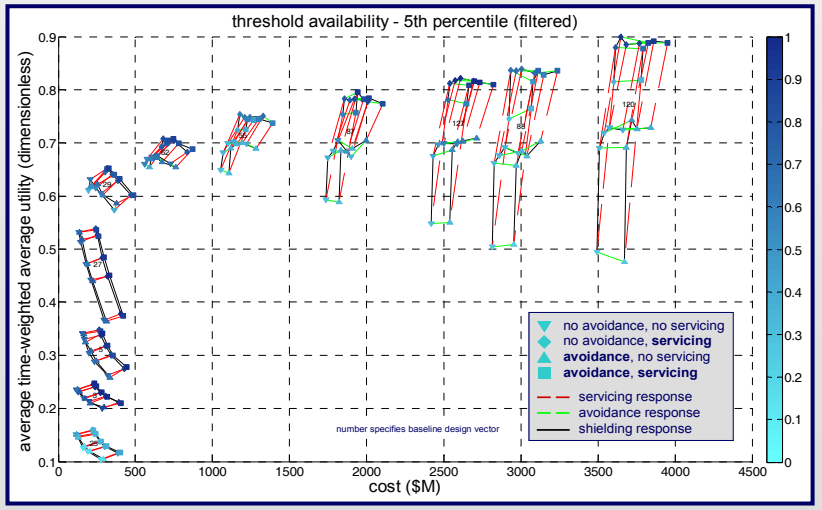
Visualization Constructs for Tradespace Exploration









Richards, M.G., Ross, A.M., Shah, N.B., and Hastings, D.E., "Metrics for Evaluating Survivability in Dynamic Multi-Attribute Tradespace Exploration," AIAA Space 2008, San Diego, CA, September 2008.

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Research Portfolio (2)

DESIGNING for VALUE ROBUSTNESS

This research area seeks to develop methods for concept exploration, architecting and design using a dynamic perspective for the purpose of realizing systems, products, and services that deliver sustained value to stakeholders in a changing world. Examples include:

- Methods for and applications of dynamic Multi-Attribute Tradespace Exploration
- Architecting principles and strategies for designing survivable systems
- Architecting strategies and quantitative tradespace exploration of systems of systems
- Quantification of the changeability of system designs
- Techniques for the consideration of unarticulated stakeholder and latent system value
- Taxonomy for enabling stakeholder dialogue on 'ilities'

Representations, analysis methods, and techniques for designing systems for "success" in dynamic contexts

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Meeting Customer Needs

- Goal of design is to create value (profits, usefulness, voice of the customer, etc…)
- Requirements capture a mapping of needs to specifications to guide design

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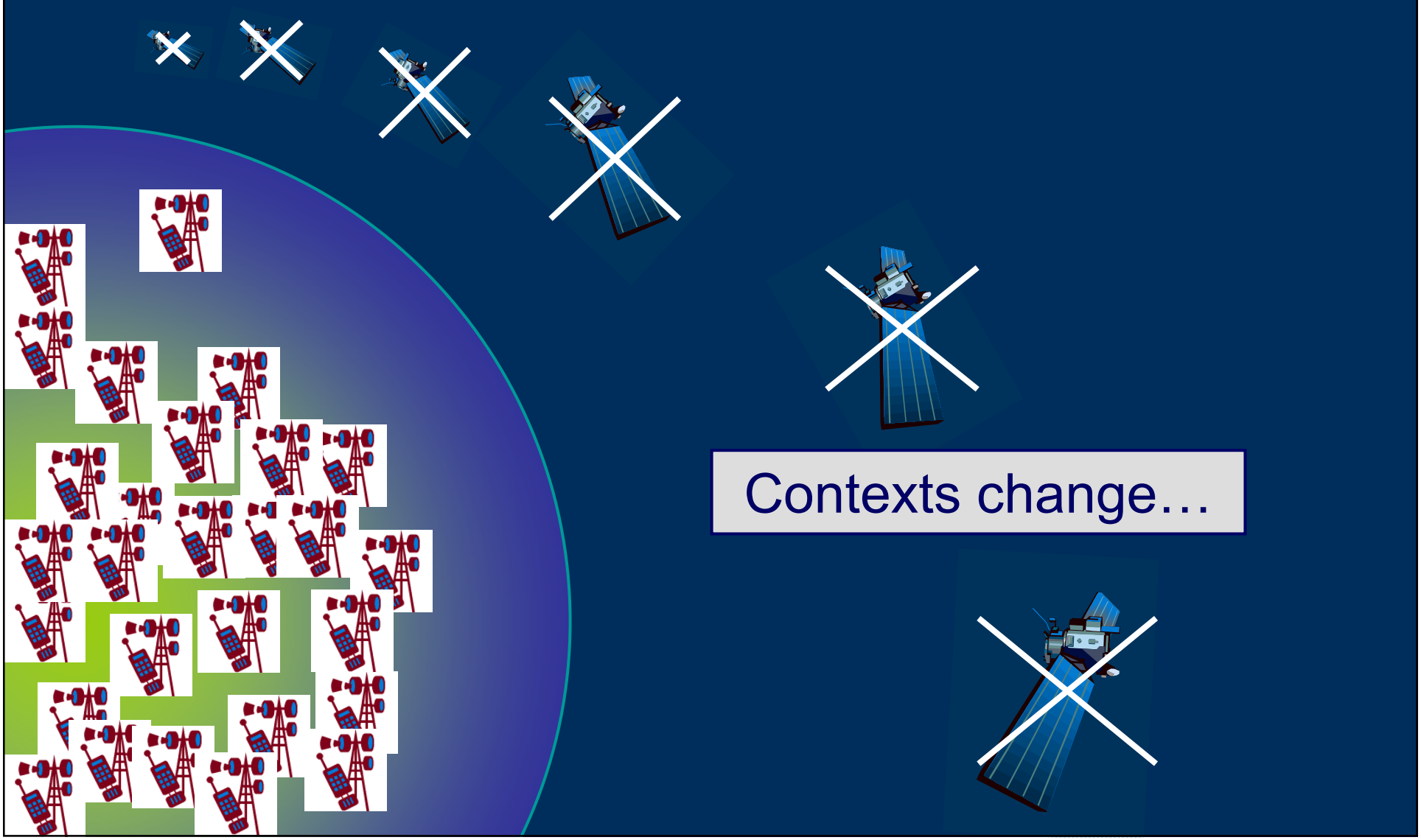
SEA RI
Systems Engineering Advancement Research Initiative

Deploying a "Valuable" System…



Contexts change…

Meeting Customer Needs (cont.)

- Goal of design is to create value (profits, usefulness, voice of the customer, etc…)
- People change their minds…
- To continue to deliver value, the systems may need to pursue changeability or versatility…

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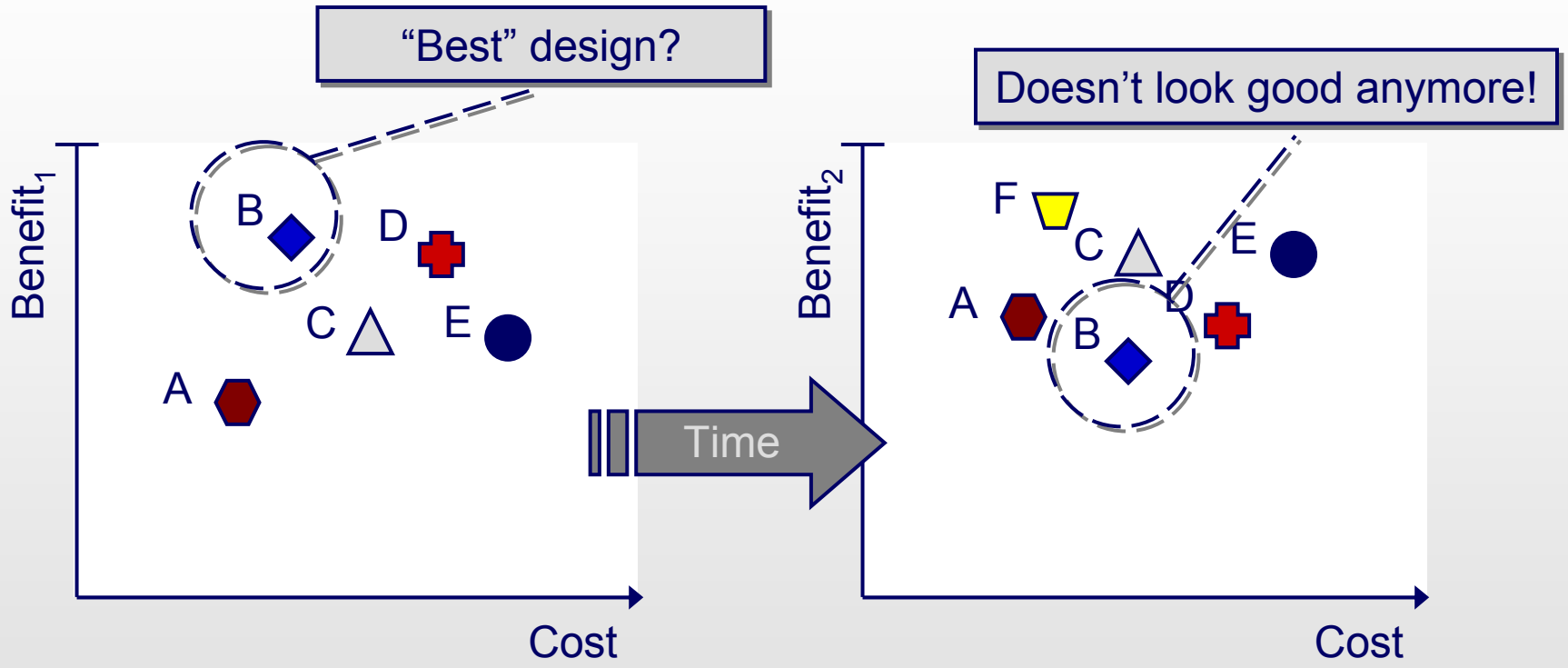
Selecting "Best" Designs



As uncertainty resolves, new contexts reveal new cost-benefit trades

How can a program select "best" designs in an uncertain and changing context?

Designing for Value Robustness directly addresses this challenge

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LAI/AF Systems Engineering for Robustness Workshop

Washington, DC in June 2004

- According to Dr. Marvin Sambur, "Systems Engineering for Robustness" means developing systems that are…

  - Capable of *adapting* to changes in mission and requirements
  - *Expandable/scalable*, and designed to accommodate growth in capability
  - Able to *reliably* function given changes in threats and environment
  - Effectively/affordably *sustainable* over their lifecycle
  - Developed using products designed for use in various *platforms* and systems
  - Easily *modified* to leverage new technologies

- "Robustness" scope expanded beyond classical robustness …
- Experts questioned…
  - What does it mean?
  - How can it be measured/analyzed?
  - Who is going to pay for it?

How can designers account for this new "robustness"?

*Adapted from Ross, A., Rhodes, D., and Hastings, D., "*Defining System Changeability: Reconciling Flexibility, Adaptability, Scalability, and Robustness for Maintaining System Lifecycle Value*," INCOSE Int'l Symposium 2007, San Diego, CA, June 2007

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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 Value Robustness
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

A.M Ross and D.H. Rhodes, "Architecting Systems for Value Robustness: Research Motivations and Progress," 2nd Annual IEEE Systems Conference, Montreal, CA, April 4-5, 2008 **BEST PAPER AWARD**

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Attribute Class Spectrum

Articulated, Unarticulated and Latent Value

Research focuses on an approach for ensuring designers account for unarticulated as well as articulated value perceptions, by intentionally building latent system value attributes according to the ease by which a system can display them

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 stakeholder and latent system value can uncover essential needs and desires early in the process
3. Observation during experimentation or early use of how stakeholders leverage latent value can be an important source of innovation

A.M Ross and D.H. Rhodes, "Using Attribute Classes to Uncover Latent Value during Conceptual Systems Design," 2nd Annual IEEE Systems Conference, Montreal, CA, April 4-5, 2008

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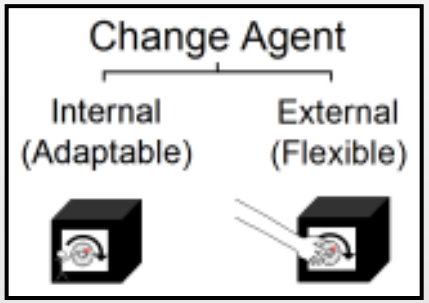
Change Taxonomy

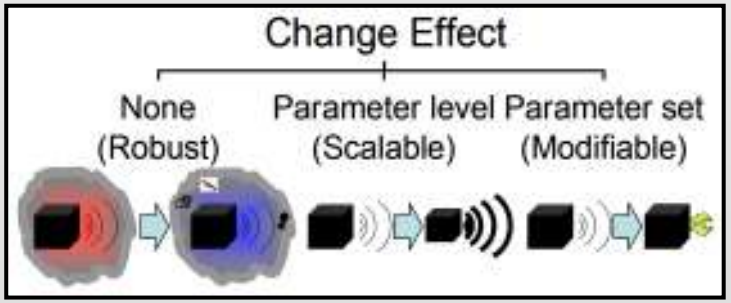
Flexibility, Adaptability, Scalability, Modifiability, etc.

Research focuses on developing a rigorous, consistent taxonomy for specifying, evaluating, and validating temporal system properties, sometimes called the "new 'ilities'"

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 and D.H. Rhodes, "Defining Changeability: Reconciling Flexibility, Adaptability, Scalability, Modifiability, and Robustness for Maintaining Lifecycle Value," *Systems Engineering*, Vol. 11, No. 3, Fall 2008, pp. 246-262

M.G. Richards, D.E. Hastings, D.H. Rhodes, and A.L. Weigel, "Defining Survivability for Engineering Systems," 5th Conference on Systems Engineering Research, Hoboken, NJ, March 2007

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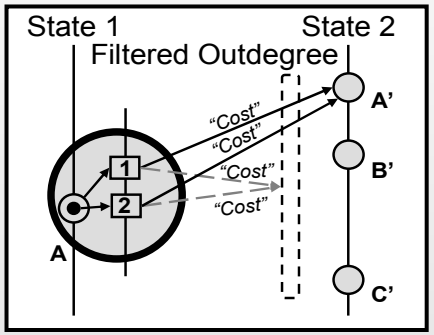
Metrics for Value Robustness

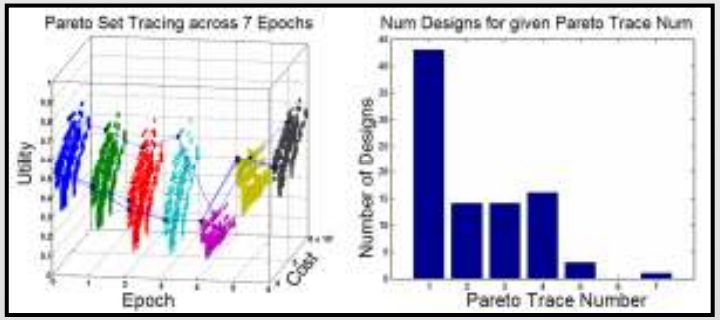
Versatility or Changeability for Maintaining Value

Research focuses on developing rigorous, quantitative metrics for evaluating and comparing, on a common basis, the ability of alternative systems to maintain value delivery over time

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





A.M Ross and D.H. Rhodes, "Defining Changeability: Reconciling Flexibility, Adaptability, Scalability, Modifiability, and Robustness for Maintaining Lifecycle Value," *Systems Engineering*, Vol. 11, No. 3, Fall 2008, pp. 246-262

N.B. Shah, L. Viscito, J.M. Wilds, A.M. Ross, and D.E. Hastings, "Quantifying Flexibility for Architecting Changeable Systems," 6th Conference on Systems Engineering Research, Los Angeles, CA, April 2008

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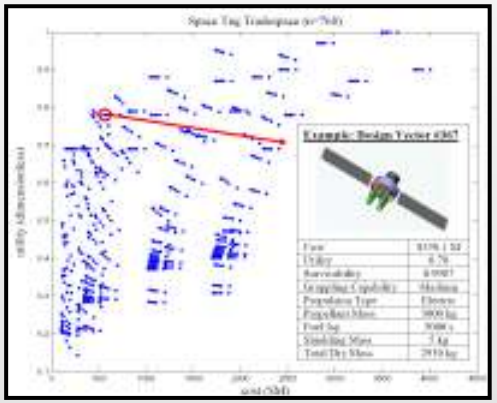
Dynamic Multi-Attribute Tradespace Exploration

Value-driven Conceptual Design for Evolving Systems

Research focuses on developing value-drive method for exploring relationship between dynamic value space and design space of many system alternatives on a common basis across time

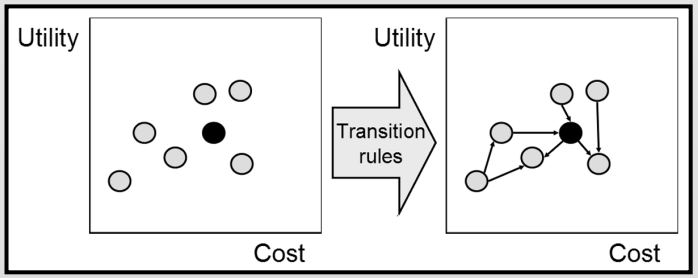
Implications for Systems Engineering Practice

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



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

- Avoids limits of local point solutions
- Maps decision maker preference structure to potential design space



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

A.M. Ross, "Managing Unarticulated Value: Changeability in Dynamic Multi-Attribute Tradespace Exploration," PhD Dissertation, MIT, June 2006

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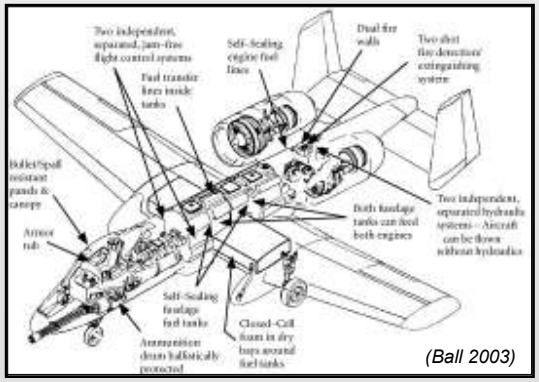
Architecting for "ilities"

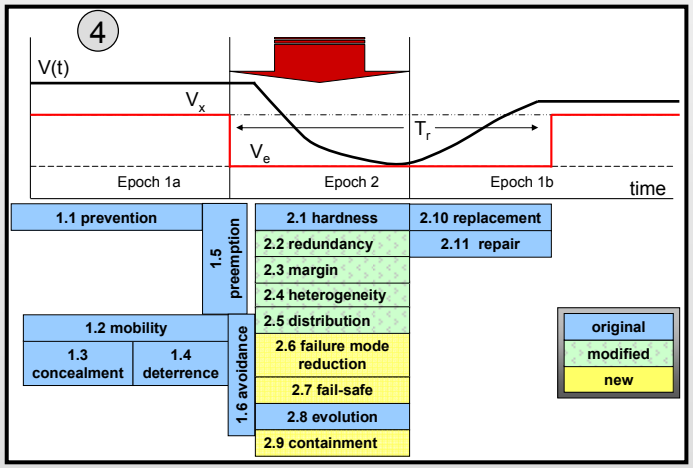
Design Principles for Dynamic System Properties

Research focuses on developing rigorous, empirically supported design principles for guiding design toward better performance in temporal system properties, such as survivability

Implications for Systems Engineering Practice

1. Validated design principles provide more rigorous guidance than classical heuristics
2. Provides a explicit mapping of design principles to timing of context events





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

M.G. Richards, A.M. Ross, D.E. Hastings, and D.H. Rhodes, "Two Empirical Tests of Design Principles for Survivable System Architecture," INCOSE International Symposium 2008, Utrecht, the Netherlands, June 2008, **BEST PAPER AWARD**

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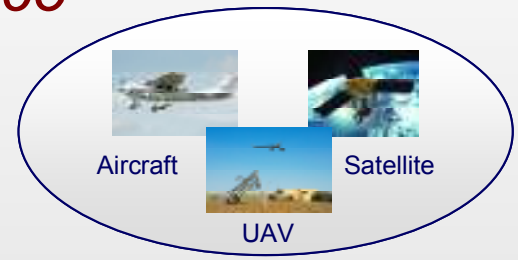
SoS Tradespace Exploration

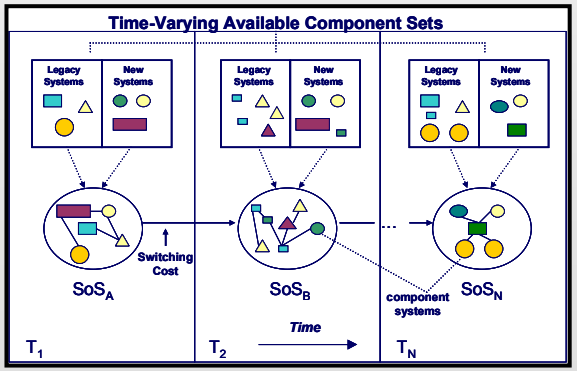
Determining SoS Components and Interfaces

Research targeted at providing a more rigorous method for system of systems engineering, which requires continuous tradespace exploration as constituent systems enter and exit the system

Implications for Systems Engineering Practice

1. Identified unique considerations for exploring SoS tradespaces versus traditional systems
2. Methods for negotiating across multiple stakeholder value propositions becomes central to successful SoS development
3. Reinforces the importance of proper interface design as essential to SoS value delivery





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

R. Valerdi, A.M. Ross, and D.H. Rhodes, "A Framework for Evolving System of Systems Engineering," *CrossTalk--The Journal of Defense Software Engineering*, October 2007

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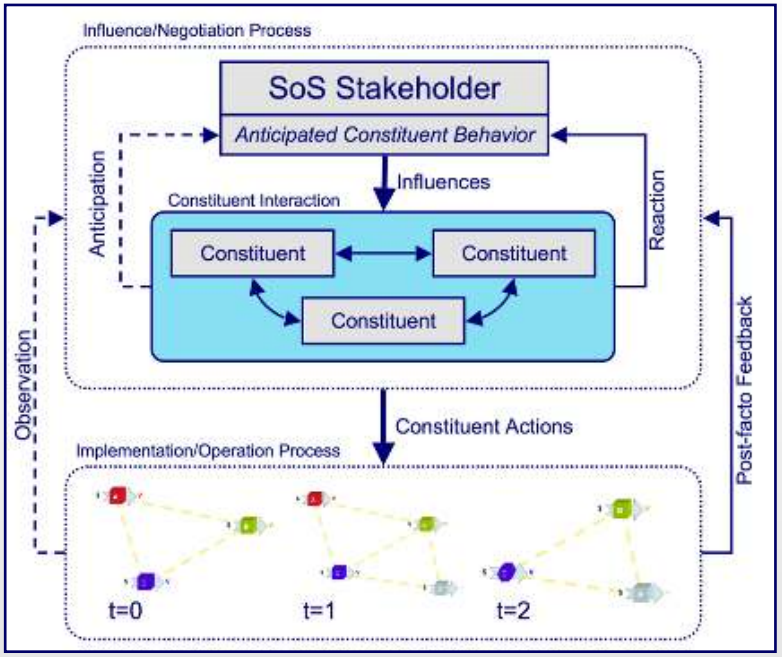
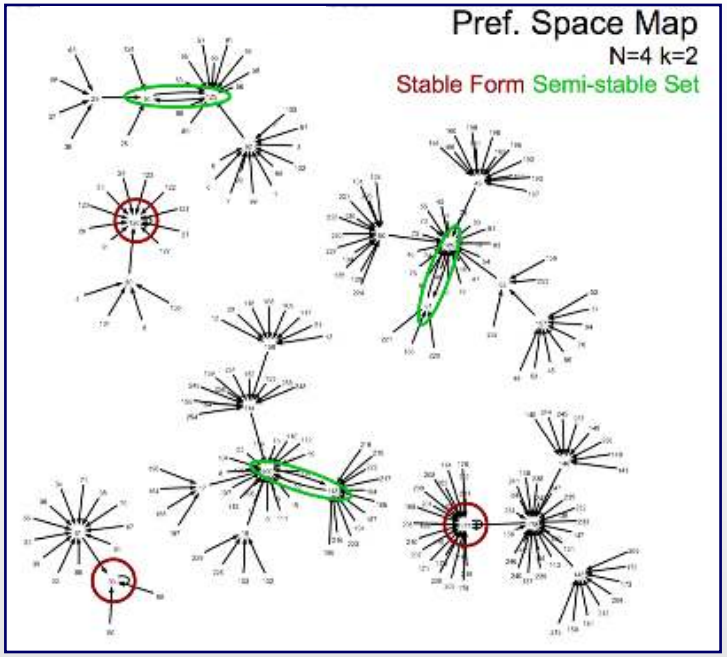
Distributed Decision Making in Systems of Systems





Extended from Schneeweiss (2003) *Distributed Decision Making*

System of System research has tended to focus on technical **interfaces** of **constituent** systems. Proper design of both technical *and* non-technical **interfaces** is essential for creating value-enhancing and stable SoS. Taking a value-centric approach reveals the importance of **distributed decision making** in SoS and mechanisms for influencing or affecting these decisions to create value robust SoS.

Nirav Shah, PhD Candidate, 2009

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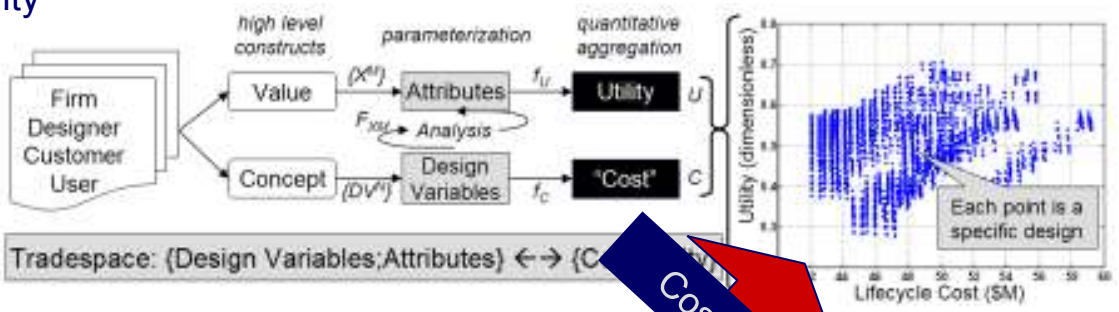
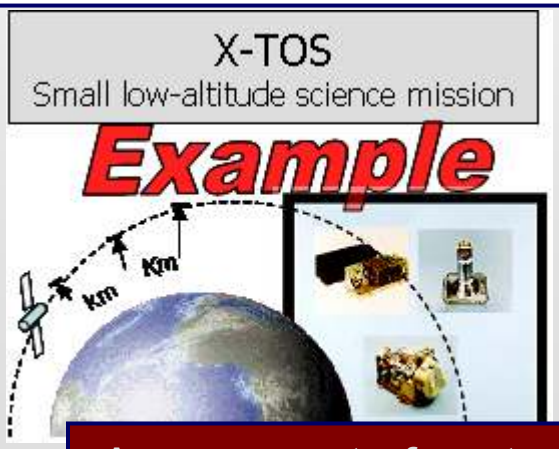
Tradespace Exploration Coupled with Value-driven Design

Many system designs can be compared through ***tradespace exploration***:

1. Elicit "Value" with attributes and utility
2. Generate "Concepts" using design variables and cost model insights
3. Develop models/sims to assess designs in terms of cost and utility

Models and simulations determine attribute "performance" of many designs (1000s to 10000s or more)





DESIGN VARIABLES:
Design trade parameters

Orbital Parameters
- Apogee Altitude (km)
- Perigee Altitude (km)
- Orbit Inclination (deg)

Spacecraft Parameters
- Antenna Gain
- Communication Architecture
- Propulsion Type
- Power Type
- Total Delta V

ATTRIBUTES:
Design decision metrics
- Data Lifespan (yrs)
- Equatorial Time (hrs/day)
- Latency (hrs)
- Latitude Diversity (deg)
- Sample Altitude (km)

Assessment of cost and utility of large space of possible system designs
Using "value" metrics focuses analysis on most important system aspects

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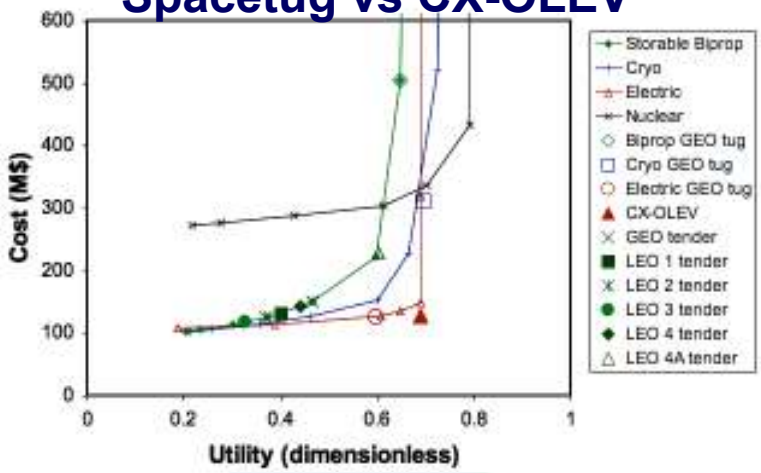
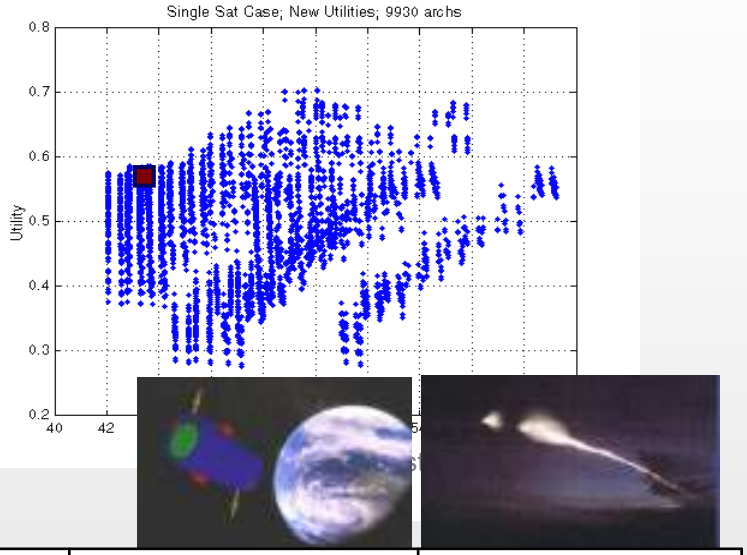
Example "Real Systems"

Spacetug vs CX-OLEV



	Electric Cruiser (2002 study)	CX-OLEV (2009 launch)
Wet Mass kg	1405	1400
Dry Mass kg	805	670*
Propellant kg	600	730*
Equipment kg	300	213*
DV m/s	12000 – 16500***	15900**
Utility	0.69	0.69
Cost	148	130*

XTOS vs Streak



	XTOS (2002 study)	Streak (Oct 2005 launch)
Wet Mass kg	325 - 450	420
Lifetime (yrs)	2.3 - 0.5	1
Orbit	300 -185 km @ 20°	321a-296p -> 200 @ 96°
LV	Minotaur	Minotaur
Utility	0.61 - 0.55	0.57 - 0.54*
Modified Utility**	0.56 - 0.50	0.59
Cost $M	75 - 72	75***
Instruments	Three (?)	Ion gauge and atomic oxygen sensor

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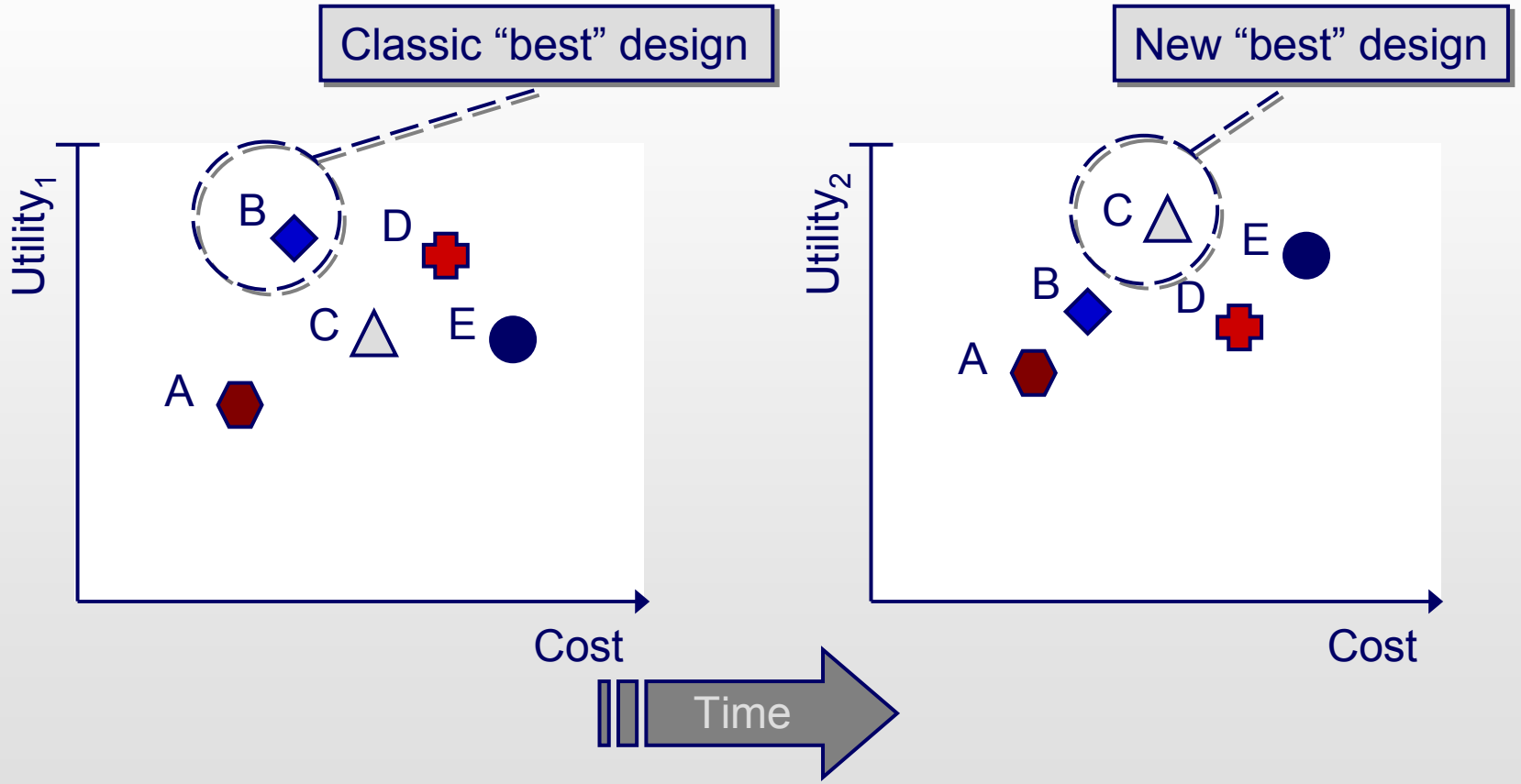
Tradespace Analysis: Selecting "best" designs



If the "best" design changes over time, how does one select the "best" design?

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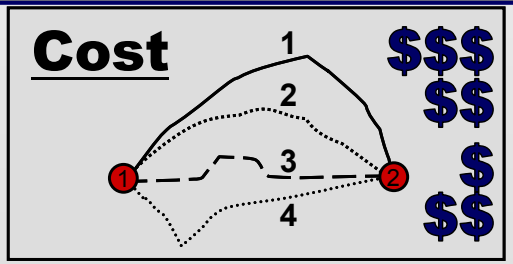
Tradespace Networks

Example: X-TOS Transition Rules

Rule	Description	Change agent origin
R1: Plane Change	Increase/decrease inclination, decrease ΔV	Internal (Adaptable)
R2: Apogee Burn	Increase/decrease apogee, decrease ΔV	Internal (Adaptable)
R3: Perigee Burn	Increase/decrease perigee, decrease ΔV	Internal (Adaptable)
R4: Plane Tug	Increase/decrease inclination, requires "tugable"	External (Flexible)
R5: Apogee Tug	Increase/decrease apogee, requires "tugable"	External (Flexible)
R6: Perigee Tug	Increase/decrease perigee, requires "tugable"	External (Flexible)
R7: Space Refuel	Increase ΔV, requires "refuelable"	External (Flexible)
R8: Add Sat	Change all orbit, ΔV	External (Flexible)

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

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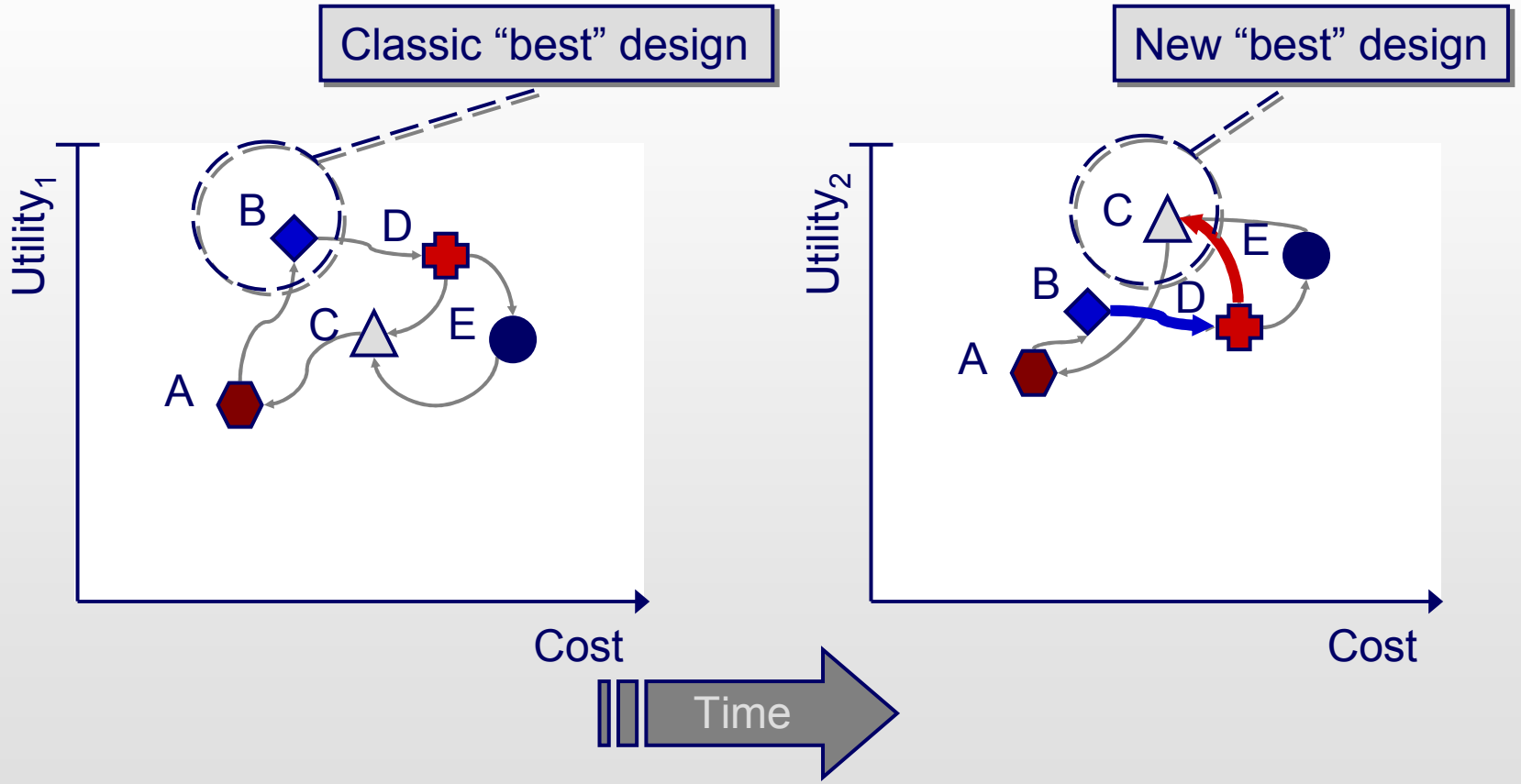
Tradespace Networks: Changing designs over time



Select changeable designs that can approximate “best” designs in new contexts

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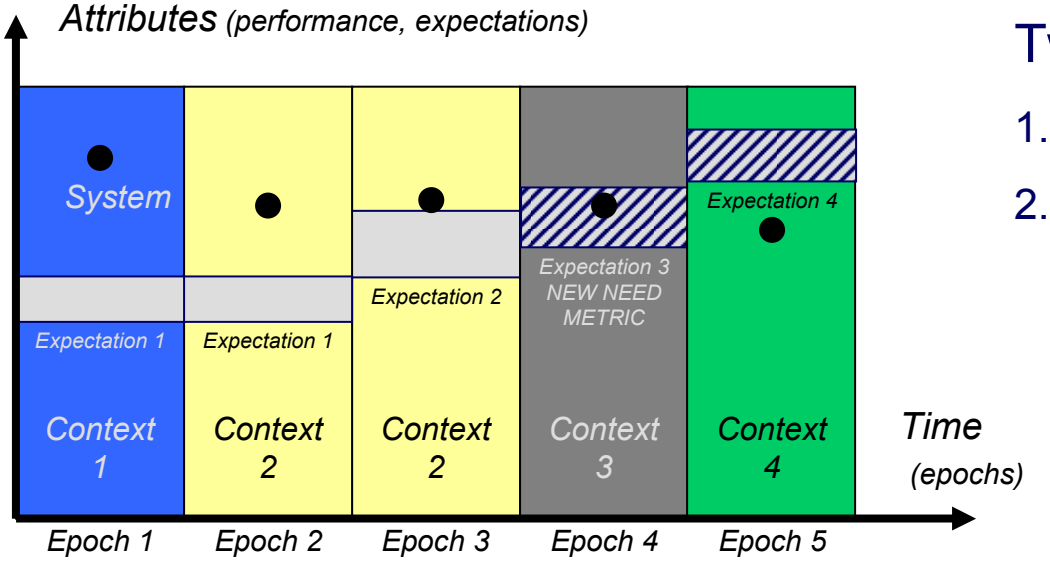
Using Epochs to Represent Contexts and Expectations

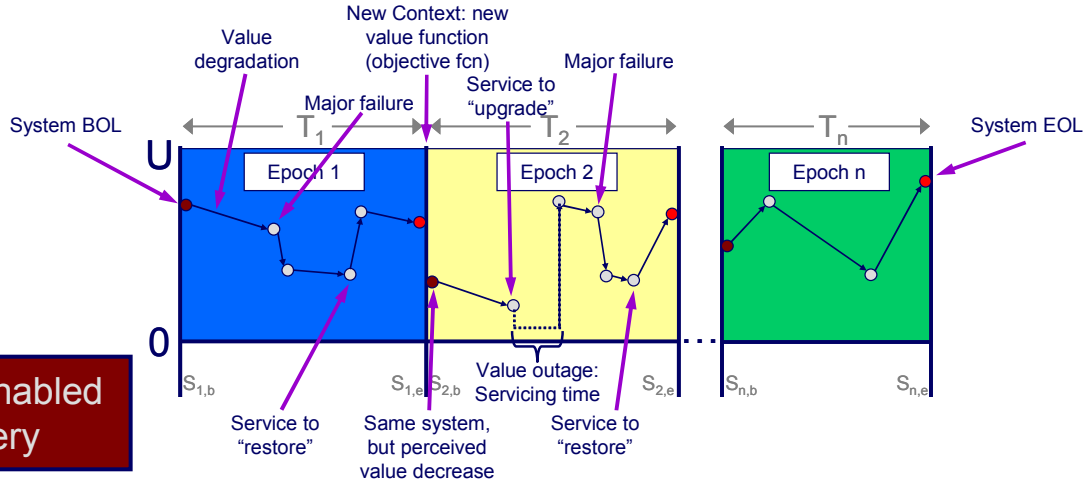


Two aspects to an ***Epoch***:

1. Needs (expectations)
2. Context (constraints including resources, technology, etc.)

Needs: + Context: …

Example system: Serviceable satellite



System timeline with "serviceability"-enabled paths allow continued value delivery

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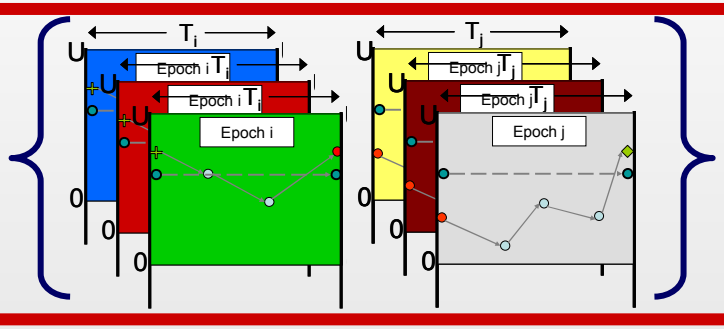
Epoch-Era Analysis: Epochs

Epoch

Time period with a fixed context and needs; characterized by static constraints, design concepts, available technologies, and articulated attributes (Ross 2006)

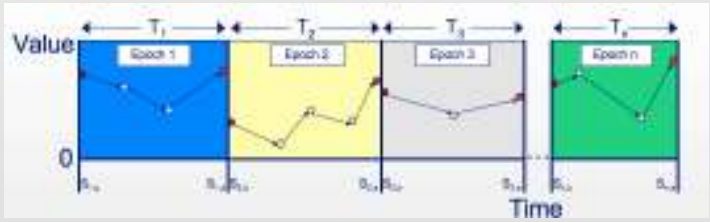
Define Epochs

- Potential Contexts
- Potential Needs



Construct Eras

- Epoch Series
- Dynamic Strategies



Discretization of change timeline into short run and long run enables analysis

Allows for rigorous consideration of many possible futures

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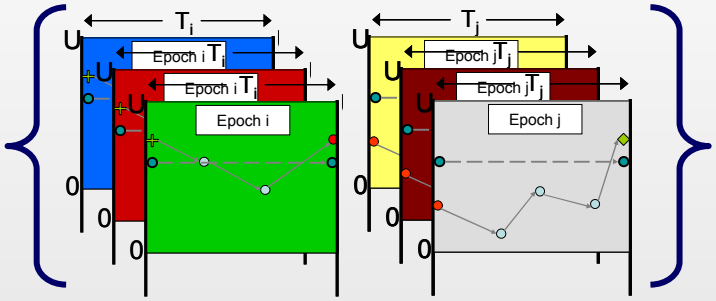
Epoch-Era Analysis: Eras

Era

System life with varying contexts and needs, formed as an ordered set of epochs; characterized by varying constraints, design concepts, available technologies, and articulated attributes

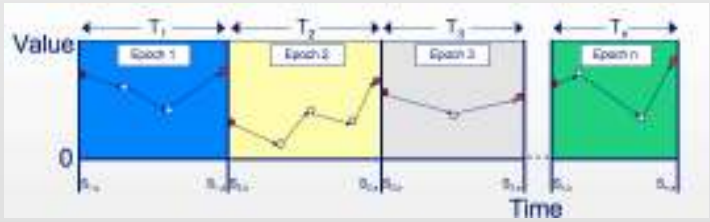
Define Epochs

- Potential Contexts
- Potential Needs



Construct Eras

- Epoch Series
- Dynamic Strategies



Discretization of change timeline into short run and long run enables analysis

Allows for analysis of system varying performance over possible futures

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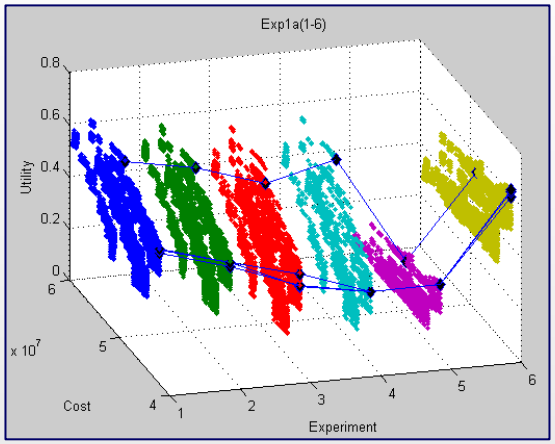
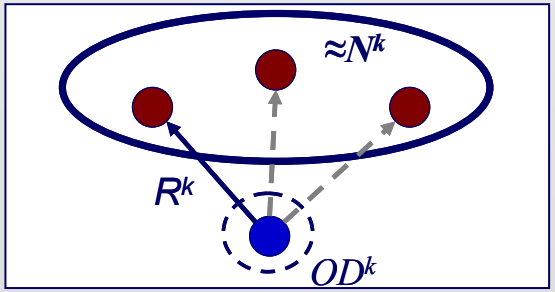
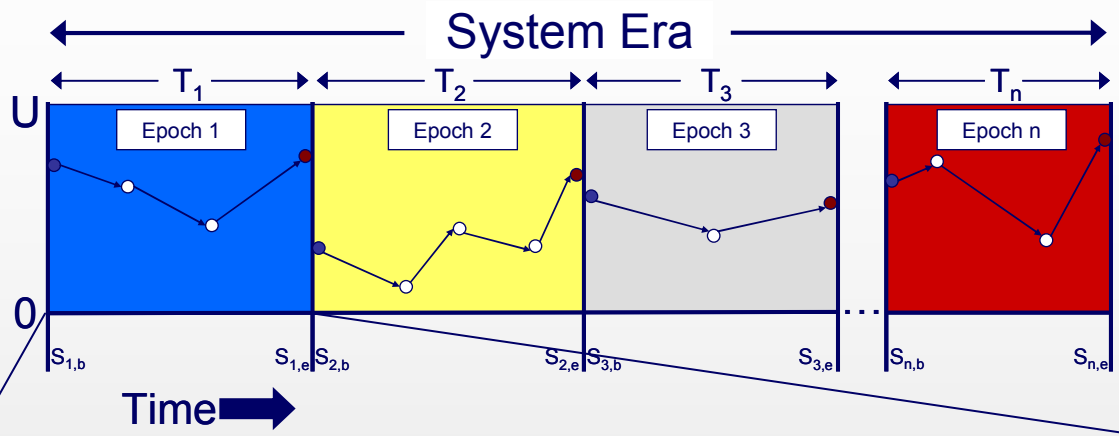
Tradespace Networks in the System Era

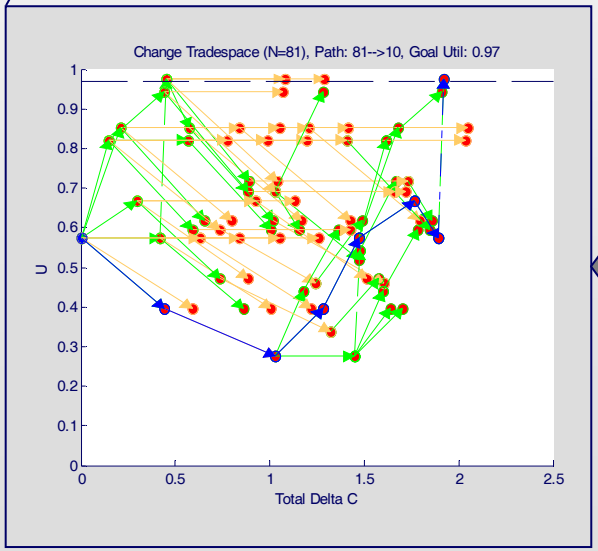
Passive Value Robustness *as* *Pareto Trace* across Epochs

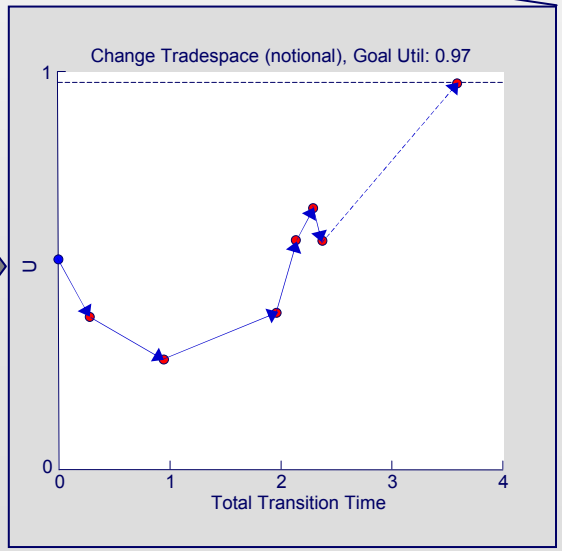


Changeability Quantified as *Filtered Outdegree*









Multiple metrics and analytic techniques available across system timeline

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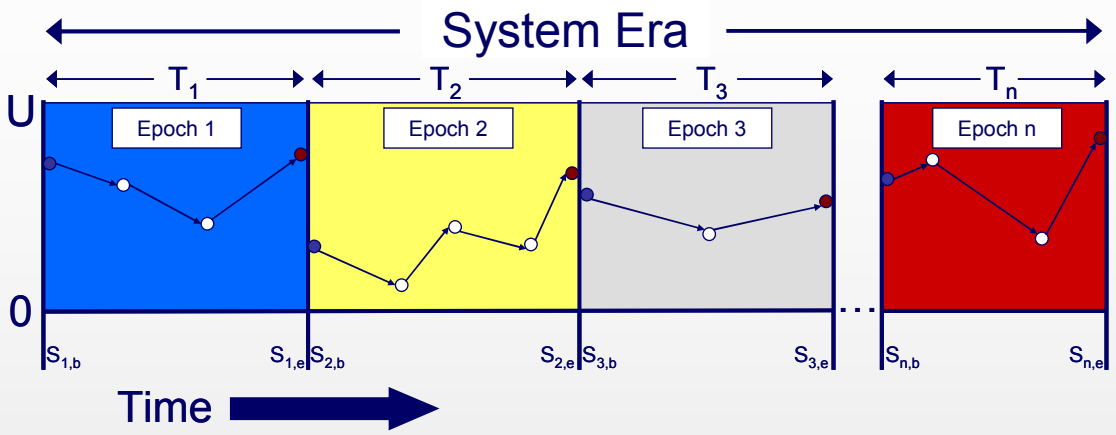
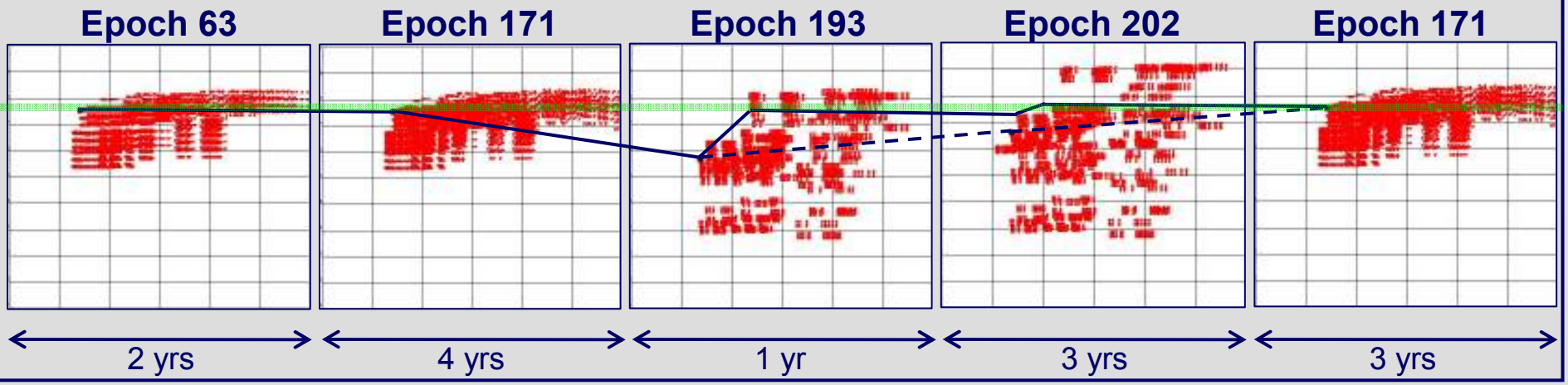
Era Paths Reveal System Evolution Strategies



Active value robustness strategy: Maintain given level of value through Context changes



Temporal strategy can be developed across networked tradespaces

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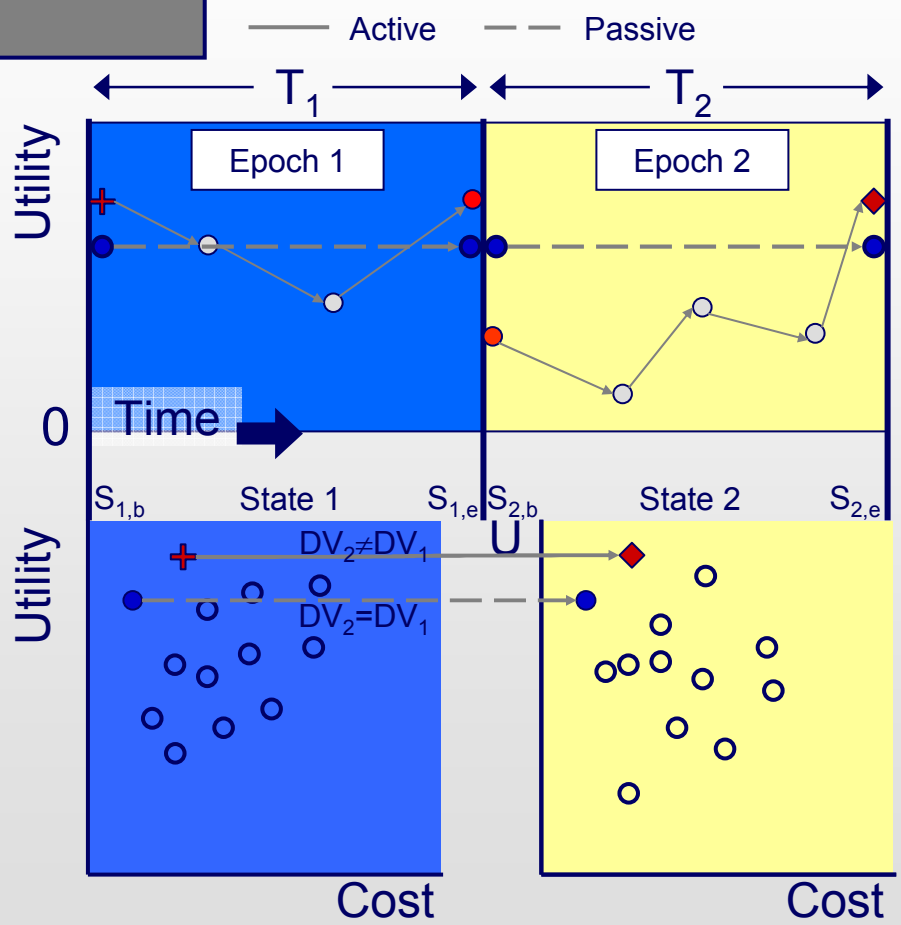
Achieving Value Robustness

Research suggests two strategies for "Value Robustness"

New Context Drivers

- External Constraints
- Design Technologies
- Value Expectations

1. Passive
   - Choose *versatile* designs that remain high value
   - Quantifiable: Pareto Trace number
2. Active
   - Choose *changeable* designs that can deliver high value when needed
   - Quantifiable: Filtered Outdegree



Value robust designs can deliver value in spite of inevitable context change

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Designing for Value Robustness

Mindshift: recognize dynamic contexts and fallacy of static preferences—the inevitability of "change"

- Two primary strategies:
  - Matching changeable systems to changing needs leads to sustained system success
  - Creating versatile systems with latent value leads to sustained system success
- Methods for increasing ***Changeability***
  - Increase number of paths (change mechanisms)
  - Lower "cost" or increase acceptability threshold (alter apparent changeability)
  - Changeability can be used as an explicit and consistent metric for designing systems
- Methods for increasing ***Versatility***
  - Increase number of displayed fundamental or combinatorial system attributes
  - Decrease "cost" for displaying or hiding attributes

Designed for changeability or versatility, systems will be empowered to become value robust, delivering value in spite of context and preference changes

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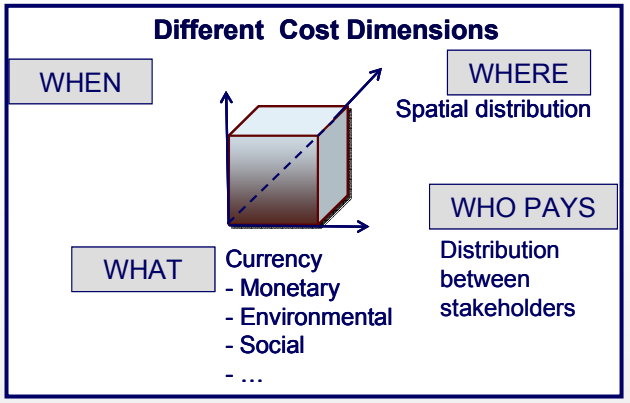
MPP Project: Applying MATE to Transportation System

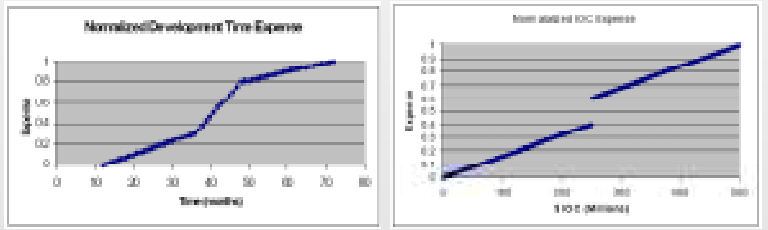
Research Questions

1. How can different "cost" types be used in tradespace studies during the planning of transportation systems?
2. How can changing environments be accounted for in sensitivity analysis of cost-benefit analysis?



- Goal: Improve Classical Cost-Benefit Analysis (CBA)
- Shortcomings of CBA
  - Time discounting and aggregation
  - Monetization of non-monetary impacts
  - Information loss of distribution impacts
  - Aggregation of impacts across stakeholders
  - Manipulation of uncertainty projections of future impacts
- Method: Apply MATE using "Expense Functions" for representing non-monetary "costs"
- Case Applications
  - Airport Express for City of Chicago
  - Portuguese Transportation project TBD

Single- Attribute Expense Functions



Diller, N.P., Utilizing Multiple Attribute Tradespace Exploration with Concurrent Design for Creating Aerospace Systems Requirements, 2002

MIT Portugal

Julia Nickel, ESD SM, Expected June 2009

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Summary

- Present-day socio-technical complexities require new academic perspectives for advancing Systems Engineering methods and tools such as
  - Visualization of complex data sets
  - Cost and benefit modeling under uncertainty
  - Value-elicitation and representation
- Engineering Systems provides a powerful “research landscape” and context for developing rigorous, cross-disciplinary systems engineering research, merging
  - Social science
  - Engineering science
  - Management science
  - Physical science

MPP ES Anchor Program provides opportunity for fundamental contributions to SE

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Questions?

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