SEA RI

Systems Engineering Advancement Research Initiative

Anticipatory Capacity:

Leveraging Model-Based Approaches to Design Systems for Dynamic Futures

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Topics

Anticipatory Capacity Defined

Anticipatory Systems

Motivations

Three Enablers

- Competencies
- Methods
- Environment

Current and Future Research

Conclusions

MIT SEAri Mission

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

What is Anticipation?

- Ability to look forward in order to take a future decision or action
- Visualization of a future event or state

The natural process of anticipation has always been a part of the design process

Systems scientists have long recognized that humans possess unique abilities for anticipation rather than simple reactive response

Anticipatory Systems

Fundamental work developed within biology and systems science:

An anticipatory system is "*a system containing a predicative model of itself and/or its environment, which allows it to change state in an instant in accord with the model's prediction of itself and/or its environment*" (Robert Rosen, 1985)

Four Characteristics of Anticipatory Systems

R. Chrisley, 2002

1. Double temporal nature of anticipations in that they are directed at one time and exist at another

2. Perturb/can be perturbed by states external to system

3. Anticipations facilitated by modeling relationship between system output, environment, future state input

4. Anticipations are organic part of system doing the anticipation

Important aspect of anticipatory systems is their dependence on predicted future states, and not only past states as would be the case for purely reactive systems

Anticipatory Capacity
designing systems

Anticipatory Capacity is the capacity to continuously develop and apply knowledge acquired through a structured approach to anticipate: (1) changing scenarios as stakeholder needs and systems context change over time; (2) to consider their consequences; and (3) to formulate design decisions in response.

Rhodes and Ross 2008

Establishing Anticipatory Capacity in Engineering Organizations

- "System" that possesses anticipatory capacity is the engineering organization performing the design of complex systems
  - Doubly temporal nature of anticipation makes it a complex process
  - Engineering organization can anticipate more than one state of system and its context at one time, and also at multiple points in time anticipate what things will be like at another

With this level of complexity only a model-based approach can provide for the level of anticipation necessary for the world of complex engineered systems

Anticipatory Capacity in Engineering Organizations

Prediction – a representation of a particular future event

Anticipation – a future oriented action, decision, or behavior based on a prediction

Anticipatory capacity provides organization with ability to make decisions based on predictive models it creates and utilizes during the design process

Models include:

- System being developed
- Environment of organizational entity doing design
- External environment in which system will operate

Value Robustness of Systems
an underlying motivation for anticipatory capacity

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

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

Motivation

Anticipatory Capacity in Engineering Organizations

Designers do an adequate job of understanding value perceptions in the short run…but to do so in the long run requires:

- effectively anticipating what the future will bring
- incorporating this knowledge into present decision

Designers can not predict the future in its entirety, but they can anticipate possible and probable scenarios for the future, and predict sequential orderings for these scenarios in order to design value robust systems

Three Enablers for Anticipatory Capacity

1. Existence of appropriate dynamic systems **competencies** in workforce

2. **Methods** for performing anticipatory thinking, analysis, and decision making in design of systems

3. Model-based **environment** to enable anticipatory design and decision making

Competencies

Four Examples

1. Ability to think deeply about systems in their context or environment

2. *Situational Leadership* – make decisions at multiple system levels and across time periods
   - Local versus global value delivery trade
   - Understanding context in which decisions are made

3. Enhanced ability to think about 'systems in time' in more rigorous and extensive manner

4. Collaborative systems thinking at team level

METHODS

two methods from MIT research

Anticipation of dynamic futures of systems at any significant depth, depends upon model-based approaches

Dynamic Multi-Attribute Tradespace Exploration

Ross, A.M., and Rhodes, D.H., "Architecting Systems for Value Robustness: Research Motivations and Progress," 2nd Annual IEEE Systems Conference, Montreal, Canada, April 2008. (Best Paper)

Epoch-Era Analysis

A.M Ross and D.H. Rhodes, “Using Natural Value-Centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis” INCOSE International Symposium 2008, Utrecht, The Netherlands, June 2008 (Best Paper)

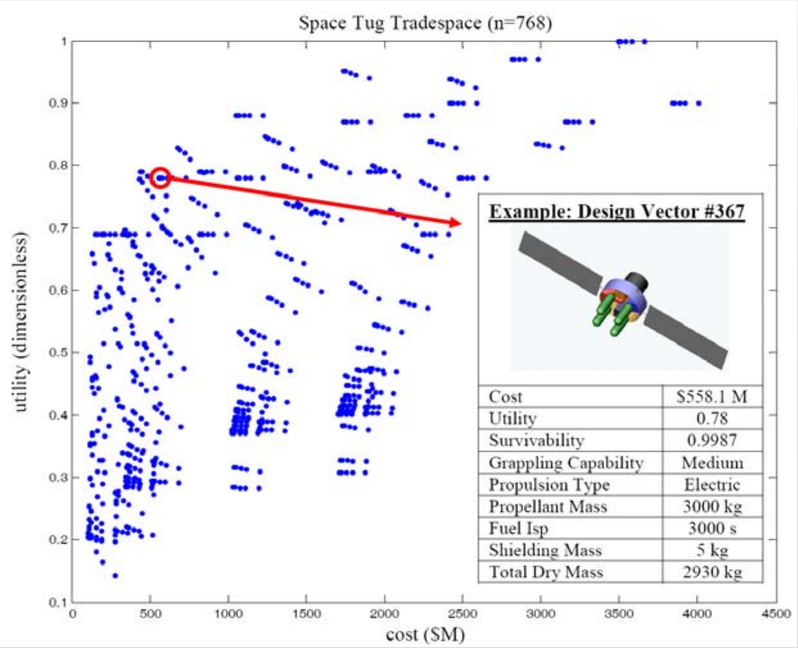
Value-Based Conceptual Design Through Tradespace Exploration

<u>Value</u> 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

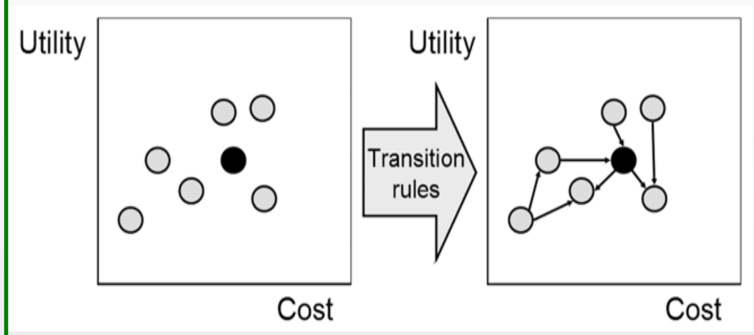
Tradespace exploration uses computer-based models to compare thousands of architectures

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



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

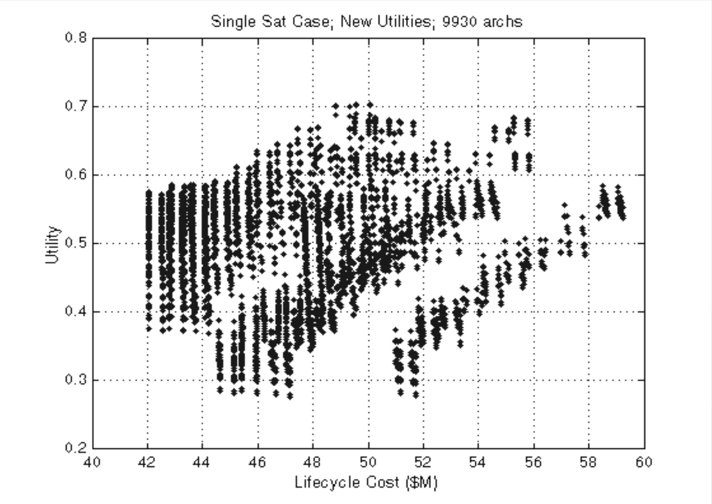
Point designs in a tradespace can be linked as a network via transition rules to assess changeability

Dynamic Multi-Attribute Tradespace Exploration Method

Implications for Systems Engineering Practice

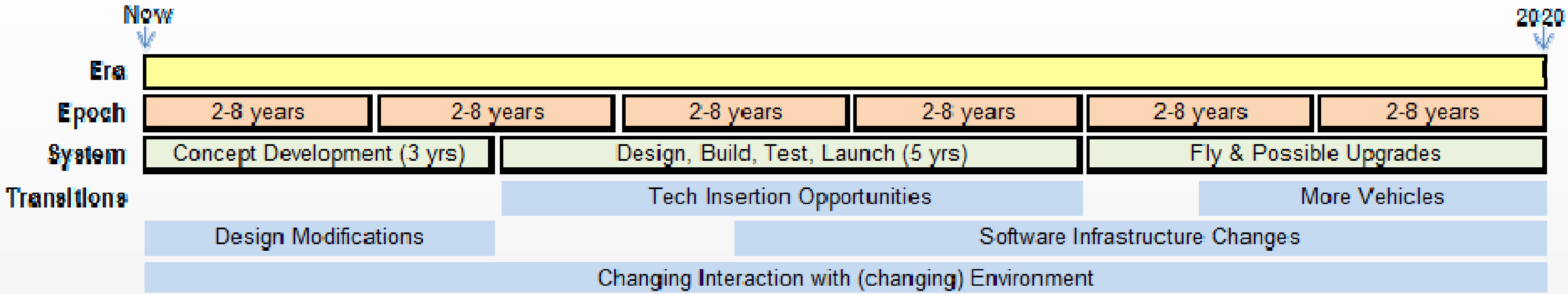
1. Ability to explore many design options and prevent too early focus on single 'point design'
2. Enables quantitative assessment of factors such as variability in technical performance and cost, and impacts in markets
3. Suitable to multiple domains and demonstrated to improve design decision making

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



Epoch-Era Analysis

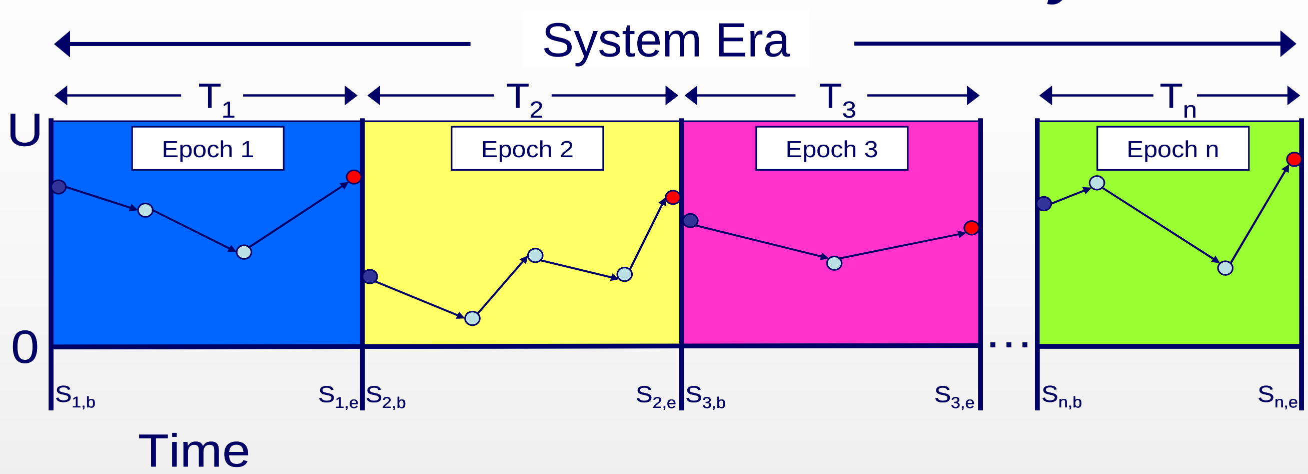
Natural Value-Centric Time Scales



- Shift in contexts occur more frequently than typical system development timelines (e.g., budgets, leadership changes, new stakeholder needs)
- Fluctuations feed back on programs, creating cost, schedule and performance risks
- By modeling system level designs and mapping their responses to context changes across the system's lifecycle phases, one can:
  - Manage how context changes effect system value delivery
  - Develop dynamic strategies that instill value robustness
  - Provide early insights into future system operational scenarios, allowing maximized system performance at less cost

Epoch-Era Analysis

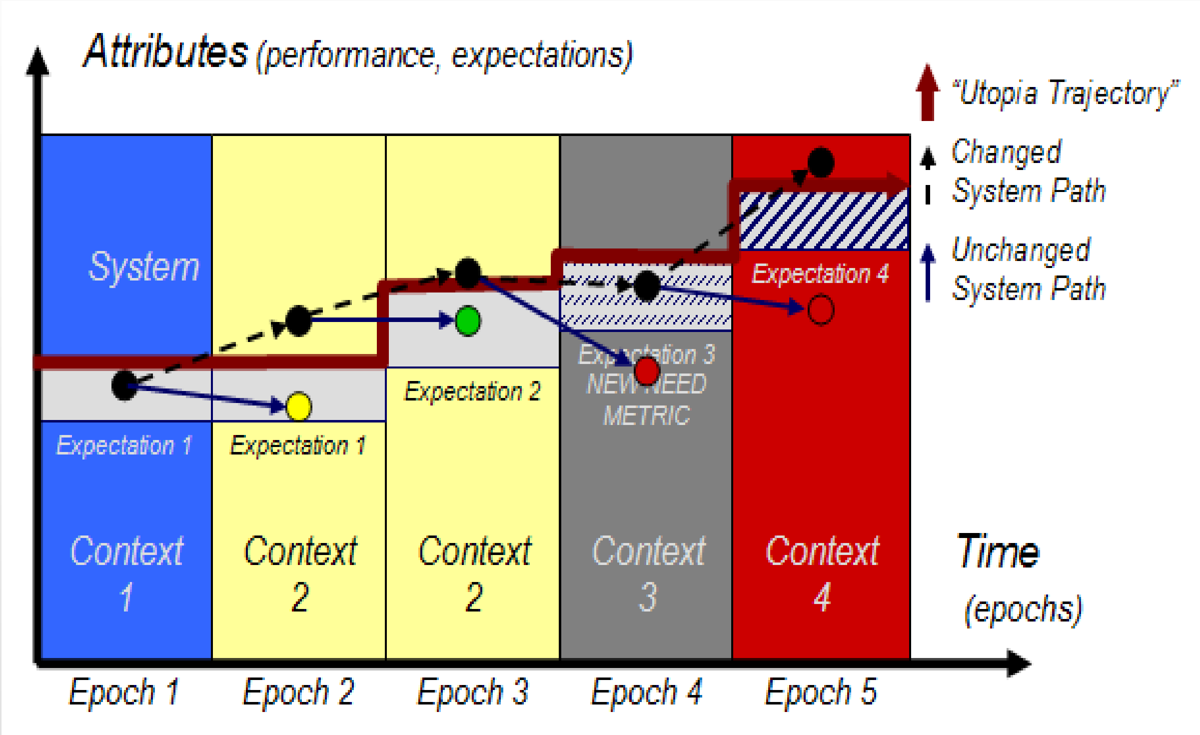
natural value-centric life cycle



- 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

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**



Dynamic Tradespace Exploration with Epoch-Era Analysis

Evaluate System Evolution Strategies

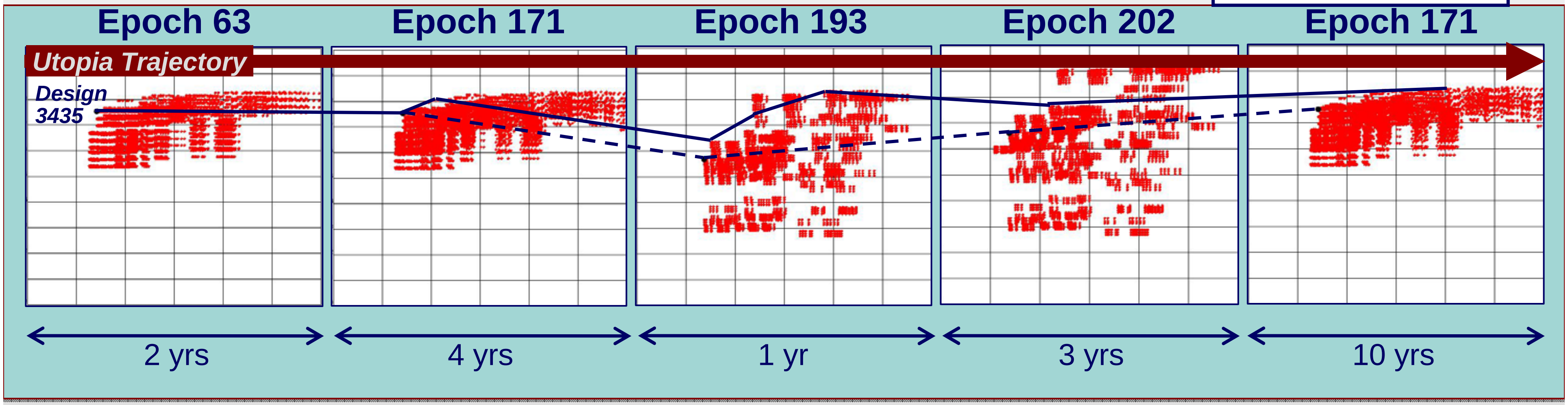
Utilize optimization approaches to derive time-based system evolution strategies that sustain / maximize stakeholder value delivery

Example strategies include:

- Maintain minimum distance from utopia trajectory
- Maximize delivered system value given a fixed budget

Key (strategy type)
Do nothing - - -
Evolve system ——

Evolution strategy: Maximize value delivery over the Era at least cost



Challenge is to find system design and transition strategy that delivers the highest value over the entire system lifecycle or within a particular context

Enabling Environment
Enhancing Anticipatory Capacity

Dynamic tradespace exploration performed by multi-disciplinary teams using model-based environments:

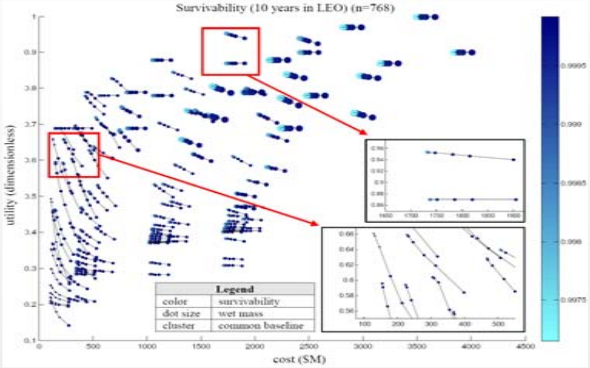
- Physical collaboration venue to bring together relevant stakeholders
- Provides computing power and toolsets need to enact anticipation methods
- Enables effective display of complex data sets and analyses to facilitate communication

Anticipatory capacity of an engineering organization will be enhanced by ….

Tradespace exploration laboratories for creating models so that dynamic futures can be elaborated and their implications considered

Research Directions

1. Further investigation of anticipation approaches applied to system design



2. Display of complex tradespace information to enable effective decision making
3. Studies of anticipation, learning and decision making in laboratory experiments
4. Discovery of how anticipations occur in collaborative systems thinking teams
5. Further research on Dynamic Multi-Attribute Tradespace Exploration with Epoch-Era Analysis

Summary

- Design process inherently involves anticipation
- *Capacity for anticipation* increasingly important with complexities of systems and environments
- Three enablers: competencies, methods, venue
- Model-based systems engineering essential for anticipatory capacity

Transitioning Research to Practice

Education

http://professionalinstitute.mit.edu

MIT Professional Institute

Value-Driven Tradespace Exploration for System Design

D. Rhodes, A. Ross, H. McManus

June 2009

MIT Campus | Cambridge, MA

Access to Research

http://seari.mit.edu