Systems Engineering Advancement Research Initiative

INCOSE 2009 SINGAPORE

20-23 July 2009

Tutorial H0A: Epoch-based Analysis: A Method for Designing Systems for Dynamic Futures

INCOSE International Symposium 2009

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About the Instructors

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- We are research scientists at MIT Engineering Systems Division (http://esd.mit.edu)
- We lead MIT's Systems Engineering Advancement Research Initiative (SEAri, http://seari.mit.edu)
- We have significant experience working both within industry and with industry
- We are principals *in The Pleiades Institute,* an education and consulting firm that disseminates MIT research outcomes and best practices we discover in that research

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Agenda

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0830	**Section 1: Intro and Motivation**
0850	**Section 2: Basics of design tradespaces**
0910	+Exercise 1
0925	-Stretch break-
0930	**Section 3: Characterizing epochs**
1000	+Exercise 2
1015	-Break-
1035	**Section 4: Performing epoch-based analysis**
1100	+Exercise 3
1115	-Stretch break-
1120	**Section 5: Advanced approach with example**
1140	**Section 6: Benefits & opportunities for epoch-based analysis**
1225	Closing comments
1230	Adjourn

Tutorial Topics

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1. Introductions and Motivations
2. Basics of Exploring Design Tradespaces
3. Characterizing System Epochs
4. Performing Epoch Based Analysis
5. Overview of Advanced Approach
6. Benefits & Opportunities for Epoch-based Analysis

MIT SEAri Research Seeks to "Change the Picture"

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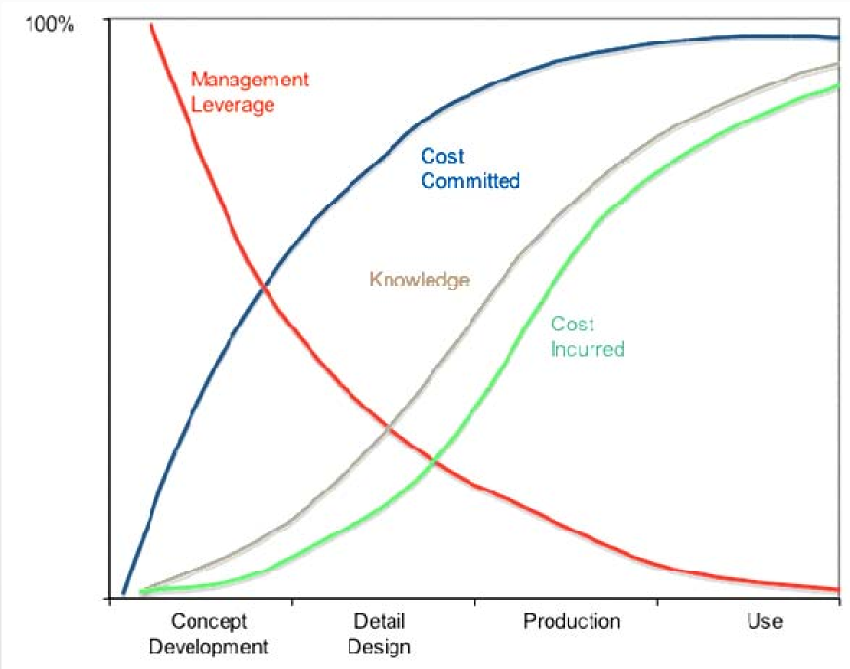

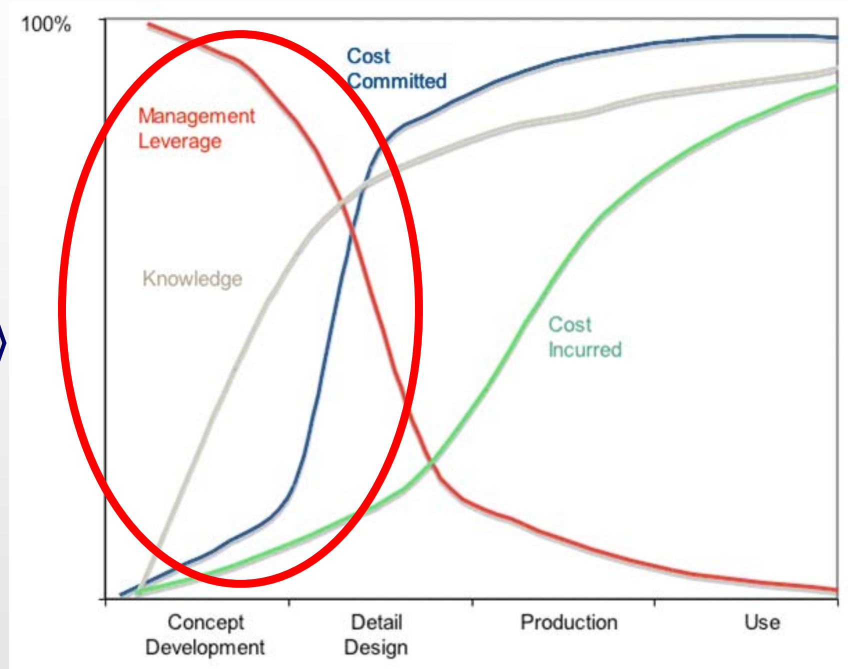

Classic decision impacts

New paradigm decision impacts

Increased knowledge (including understanding of uncertainties) allows better decisions

1. Introduction and Motivations

Contemporary Engineering Environment

- Unprecedented levels of complexity
- Global engineering environment
- Complex societal problems
- Important lifecycle properties
- From products to services
- From single system to system families
- Rapid innovations in technologies
- Strong emphasis on interoperability
- Network centric paradigm
- Fast paced environment

Motivation

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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

What is Anticipation?

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- 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

Epoch-based Analysis is an approach for anticipating dynamic futures and designing systems accordingly

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

Three Enablers for Anticipatory Capacity

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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

Rhodes, D.H. and Ross, A.M., "Anticipatory Capacity: Leveraging Model-Based Approaches to Design Systems for Dynamic Futures," 2nd Annual Conference on Model-based Systems, Haiffa, Israel, March 2009

2. Basics of Exploring Design Tradespaces

Making Design Decisions

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At a fundamental level, design is about constrained “choice”

- Designers: choice of tools, concepts, colleagues, work hours, technology, etc.
- Users: CONOPS, reflected needs, anticipated needs, risk aversion and gaming, etc.
- Customers: benefit at cost, whose benefit, time value of money, etc.

How can design be improved through a “choice” point of view?

So design is about choice?

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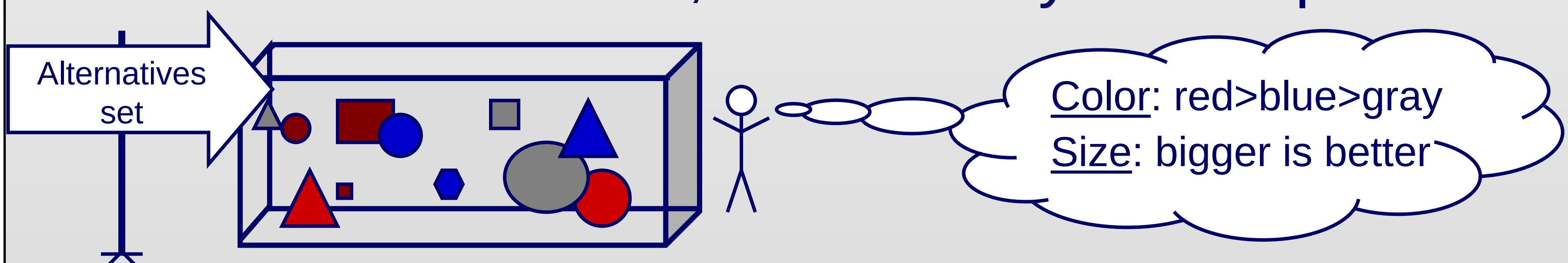
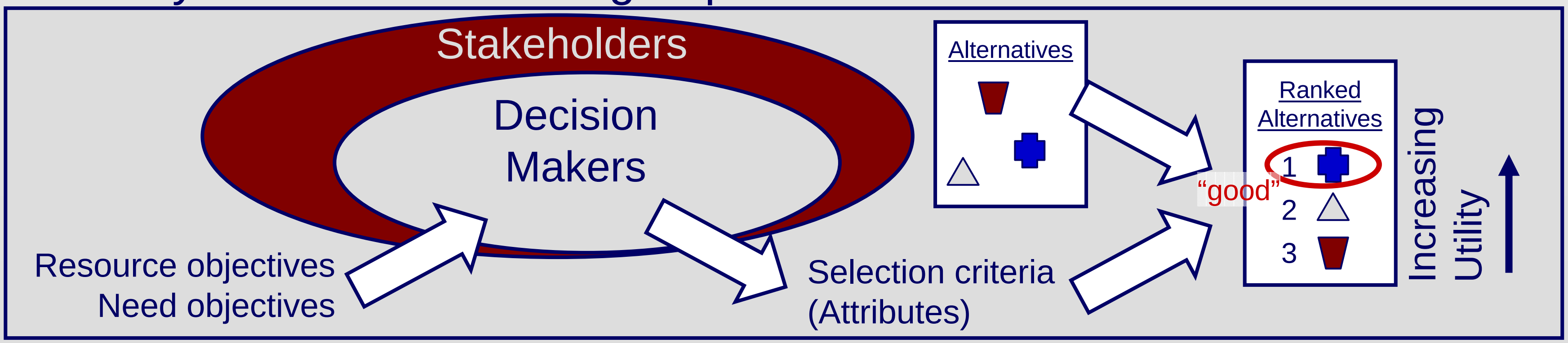
- "Choice" making a selection from a set of alternatives
- Classical decision theory concerns this problem
- Design encompasses a special class of decision problems: "wicked"
  - Open set of alternatives (infinite(?) possibilities)
  - Multi-criteria selection rule (multiple goals)
- Not a well-defined, theoretically solved problem…



Actually "Design" is about creating "good" alternatives

Stakeholders-Attributes-Utilities

- In order to ensure a successful mission, the implied value proposition must be fulfilled
- Each system **stakeholder** has a value proposition—what they want to "get out" of the mission
- Decision makers are stakeholders with influence over the mission objectives for needs and/or resources
- Meeting the objectives for each decision maker can be assessed in terms of "**attributes**"
- An alternative that scores well in a set of attributes gives a decision maker value, or "**utility**"
- The goal for the selection of a good alternative is to maximize the utility for individuals and groups



Tradespace Exploration: Identifying Valuable Designs

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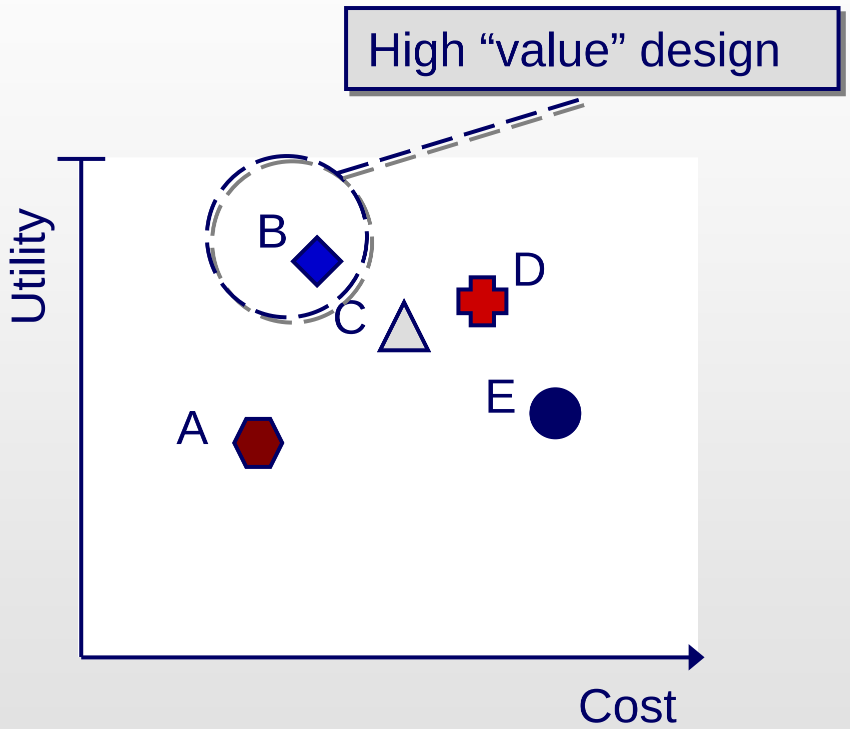

Using "Utility" and "Cost" metrics, one can identify high "value" designs

Meeting Customer Needs

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- 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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Deploying a "Valuable" System…

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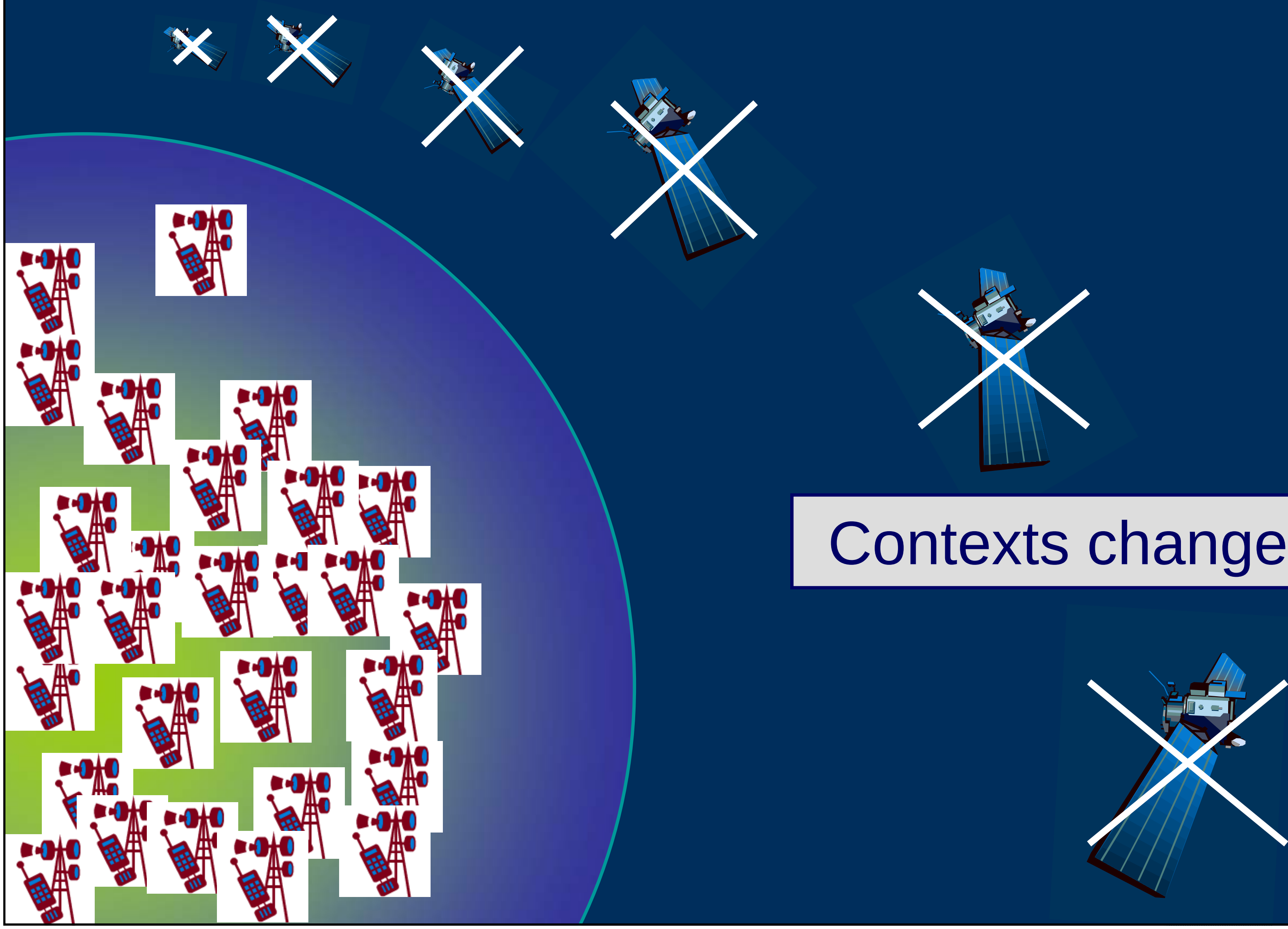

Contexts change…

Meeting Customer Needs (cont.)

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- Goal of design is to create value (profits, usefulness, voice of the customer, etc…)
- People change their minds…
- To continue to deliver value, the definition of system success may need to change as well…

What is System Success?

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Success is defined across multiple time periods and multiple perspectives

System success, Ψ, across N decision makers at time t

Net "experience" Net "expectations"

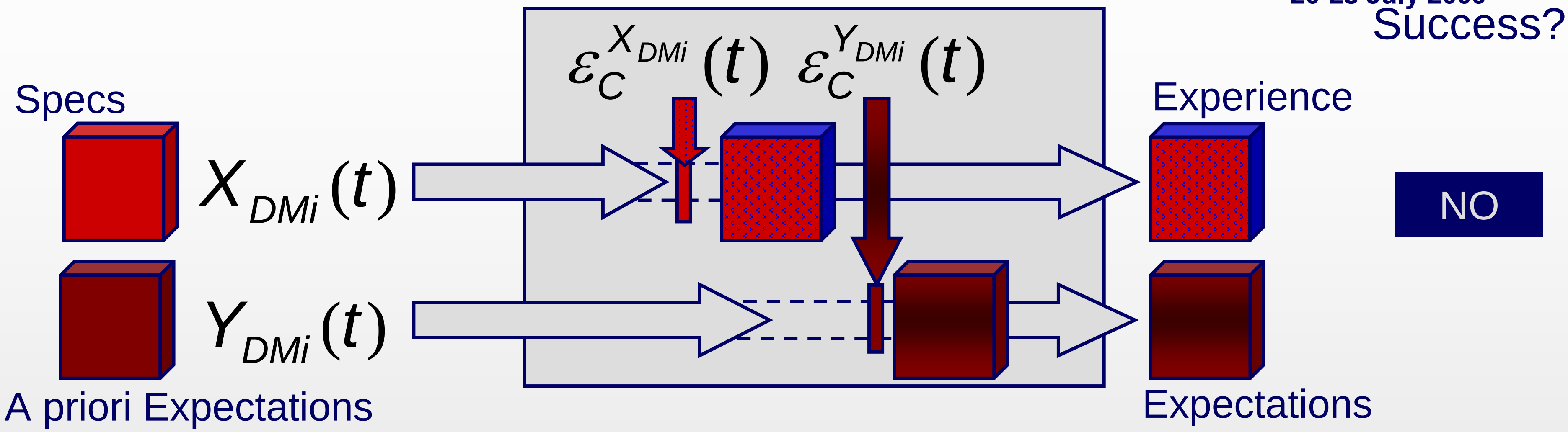
$$\Psi(t) = \sum_{i=1}^{N} \left[X_{DMi}(t) + \varepsilon_C^{X_{DMi}}(t) \geq Y_{DMi}(t) + \varepsilon_C^{Y_{DMi}}(t) \right]$$

$$0 \leq \Psi(t) \leq N$$

$X_{DMi}(t)$	Decision maker i unaffected system "experience" at time t	$\varepsilon_C^{X_{DMi}}(t)$	Context effect on decision maker i "experience" at time t
$Y_{DMi}(t)$	Decision maker i unaffected system "expectation" at time t	$\varepsilon_C^{Y_{DMi}}(t)$	Context effect on decision maker i "expectation" at time t

System Success: Net "experience" must meet or exceed net "expectations"

What is Context?



- Context includes forces exogenous to system
  - "Other" stakeholder expectations
  - Operating environment
  - Policy constraints
  - Available technologies
  - Competitors in market
  - Etc…
- System success depends on system performance within a given *context*
- In order to ensure success, designers must consider context beyond traditional "operating environment" (classical robust design)

The Dynamic Value Problem

- System designers and architects often face changes in…
  - User needs
  - Available technologies
  - Political and technical contexts
- Classical "scenario analysis" can be too opportunistic, qualitative, or sparse
- Systems must be able to deliver value in spite of changes in context and needs
  - Strategy one: "Changeable" systems (*i.e.*, use "ilities' in architecture)
  - Strategy two: "Versatile" systems (*i.e.*, build in "extra" value)
- Structured method needed for collecting information to characterize and evaluate systems across a wide variety of possible futures

How can alternatives be evaluated across changing contexts and needs?

Tradespace Analysis: Selecting "Best" Designs

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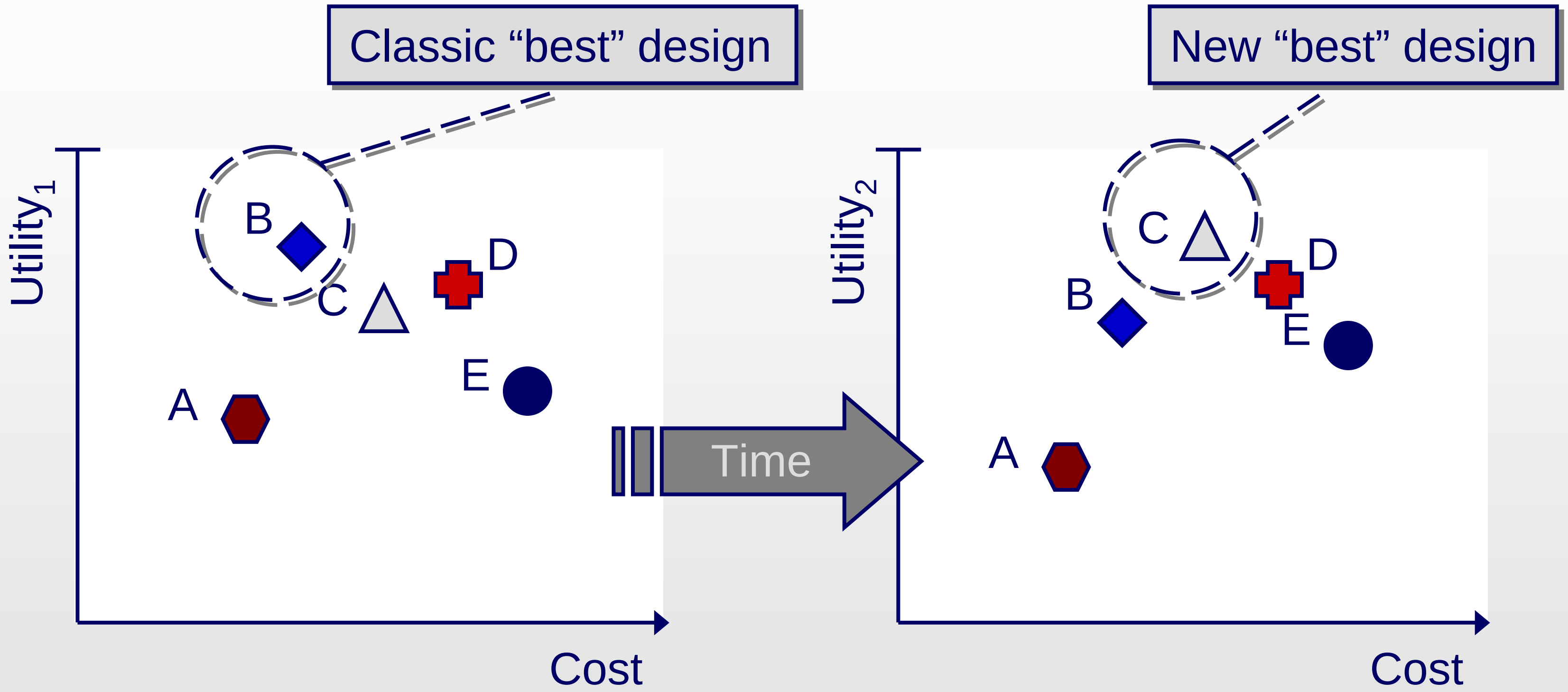

If the "best" design changes over time, how does one select the "best" design?

Tradespace Analysis: Identifying "Good" Designs

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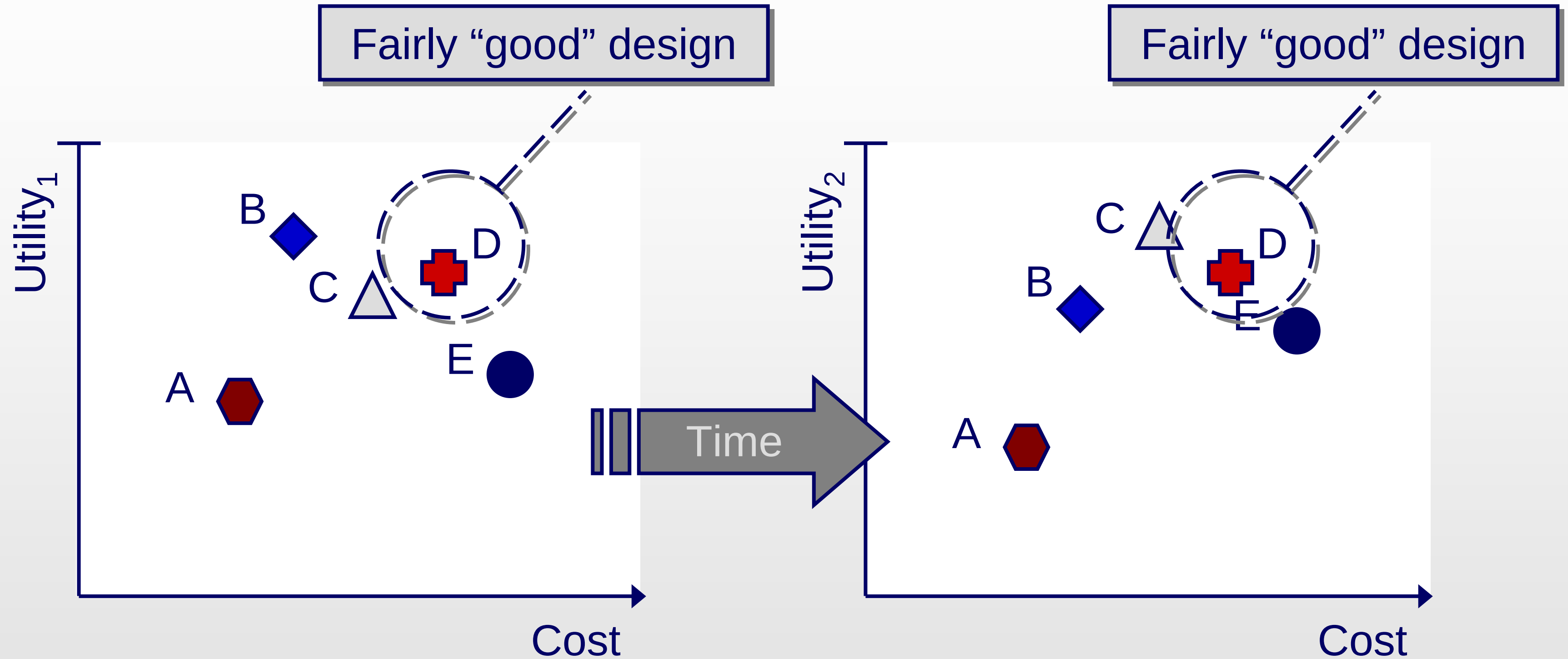


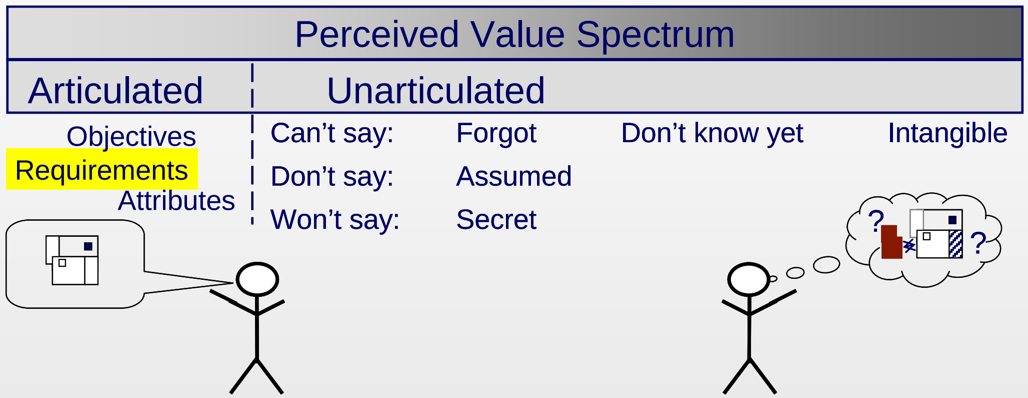
Designs that maintain value delivery in spite of changes in needs or contexts are called *value robust**

*if no system changes are required, then it is "passively value robust"

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

"Good", or "satisficing", designs can be identified across changing objectives

Exercise One



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3. Characterizing System Epochs

Traditional Perspective

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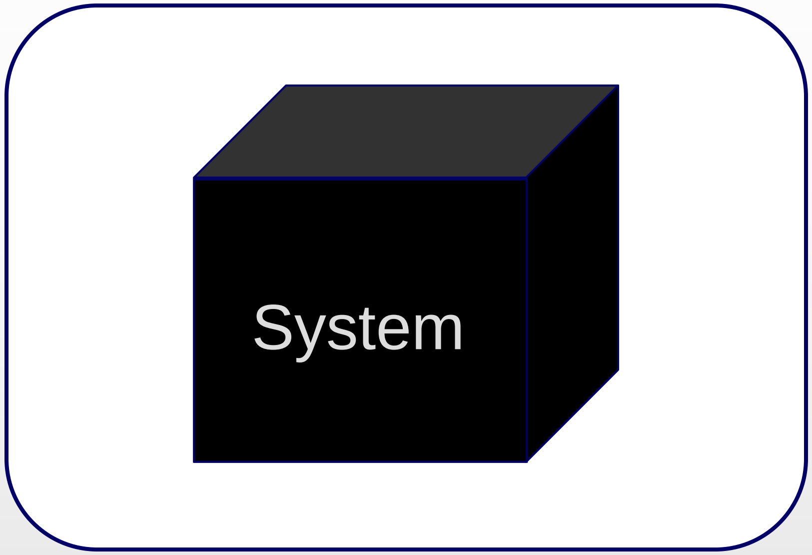


- Does my System…
  - have good requirements? (stable, achievable, verifiable, etc. across many use-cases, stakeholders, and environments)
  - meet the requirements?
- Does my System program have acceptable…
  - cost, schedule, risk, etc…?

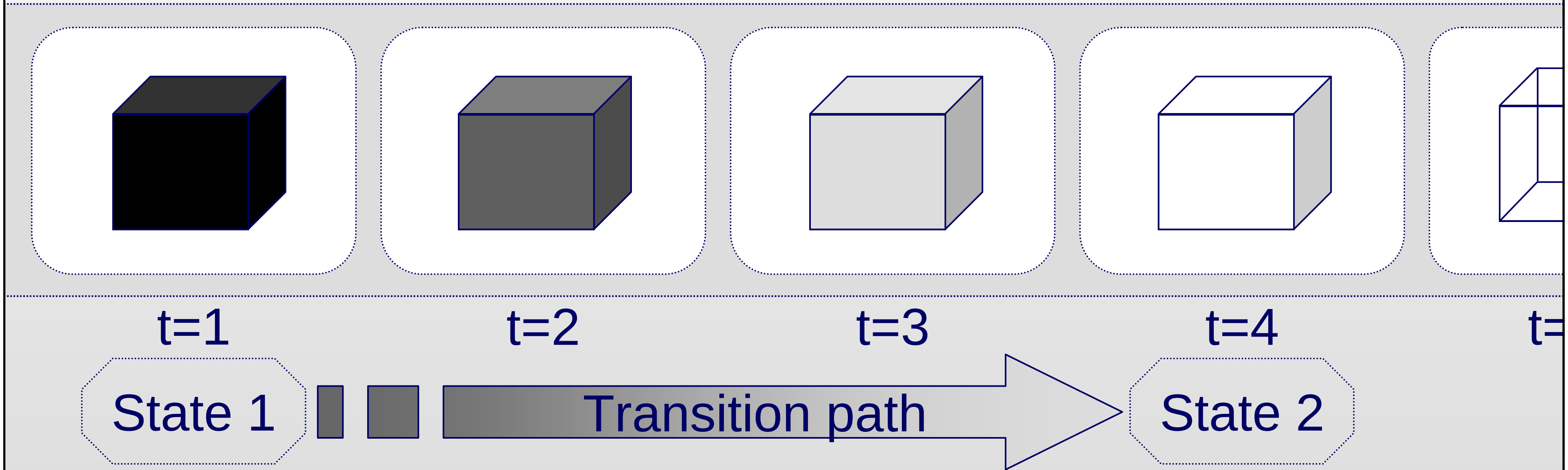
Changes are considered to be "bad"

Inherently a "static" perspective, but methods bias us in this direction

From Static to Dynamic Views

If classical approaches bias us in the direction of a static perspective, how can we move closer to a dynamic reality?

View time as a movie reel (series of static boxes)



A string of static analyses can approximate dynamic analyses, in the limit

The System Change Timeline

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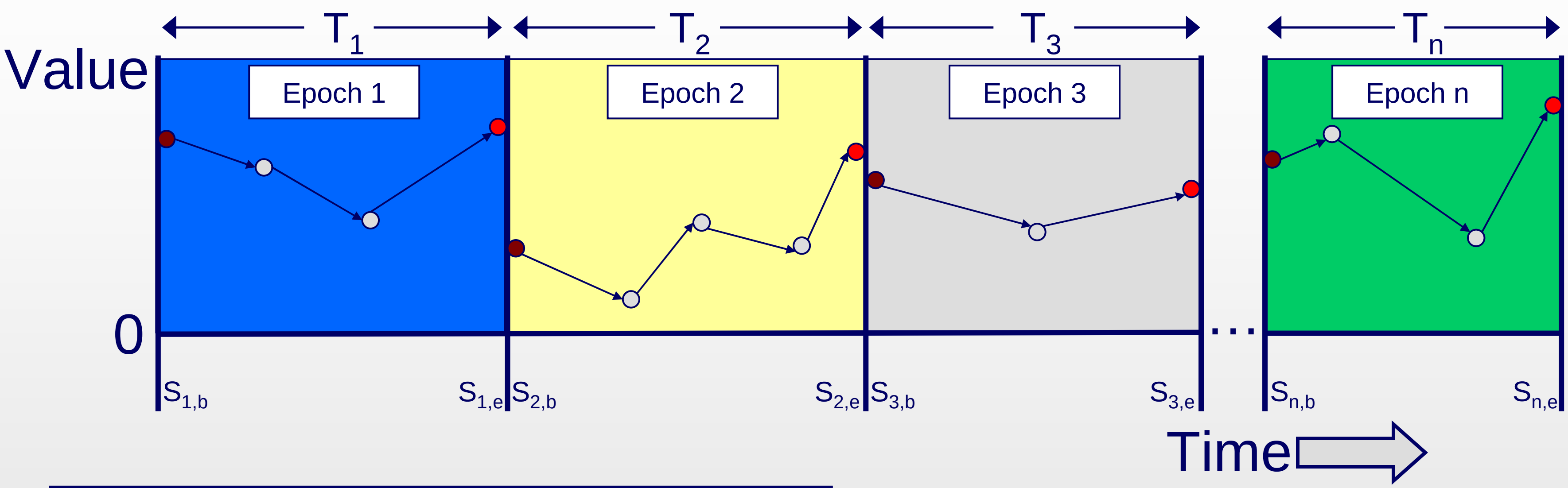

Epoch

Time period with a fixed "context"

Fixed: Constraints, design concepts, available technology, and expectations (attributes and utility function)

One Epoch: short run
Multiple Epochs (System Era): long run

Epoch Purpose

Partition problem into series of short run problems

Legend:

T_i: Duration of Epoch i

$S_{i,b}$,$S_{i,e}$: System State at beginning,end of Epoch i

Continuity of States: $S_{i,e}=S_{i+1,b}$

Epoch-Era Analysis for Generating Future Scenarios

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Compare Alternatives

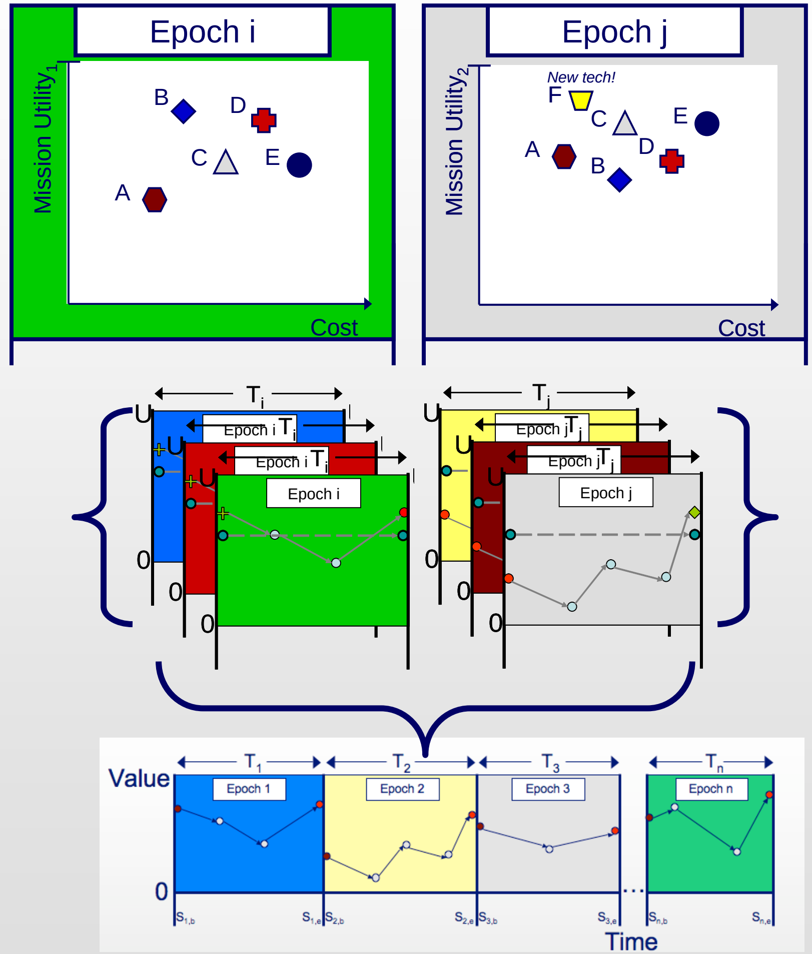
Static tradespaces compare alternatives for fixed context and needs (per Epoch)

Define Epochs

Epoch set represents potential fixed contexts and needs

Construct Eras

Eras represent ordered epoch series for analyzing system evolution strategies



Parameterizing future contexts allows for generating ensembles of scenarios

Epoch Characterization

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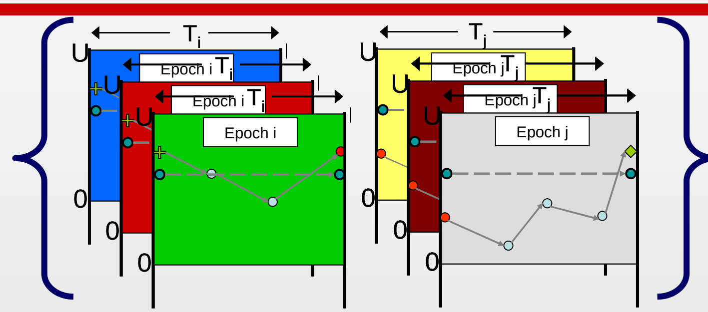
Definition of Epoch:

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

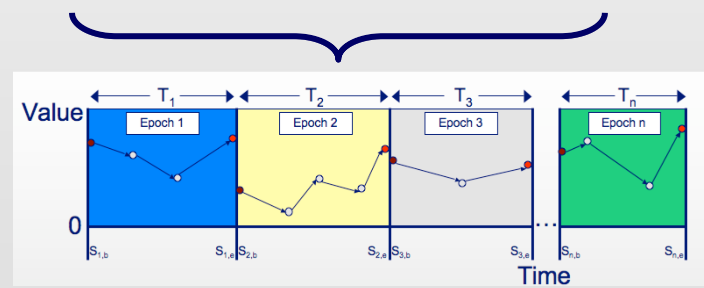
Define Epochs

- Potential Contexts
- Potential Needs



Construct Eras

- Epoch Series
- Dynamic Strategies



Parameterize future contexts for generating and sampling scenarios

Using Epochs to Represent Context and Expectations

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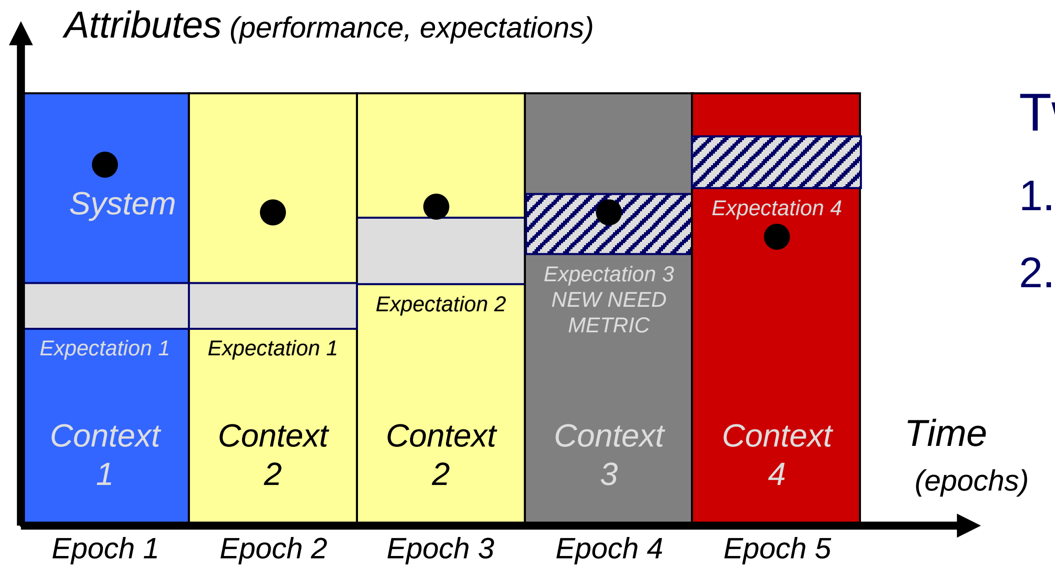
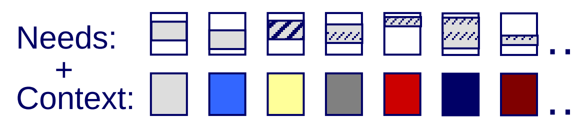
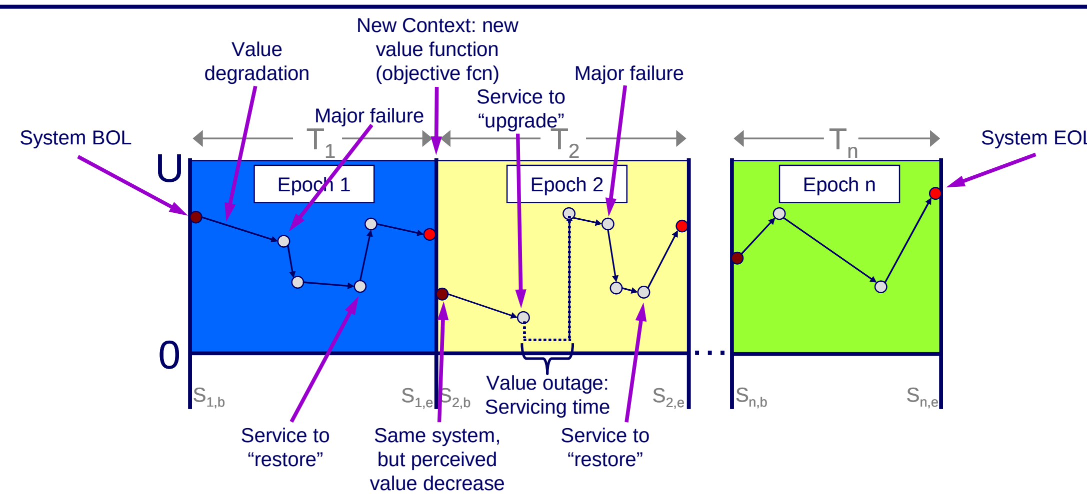


Two aspects to an ***Epoch***:

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



Example system: Serviceable satellite



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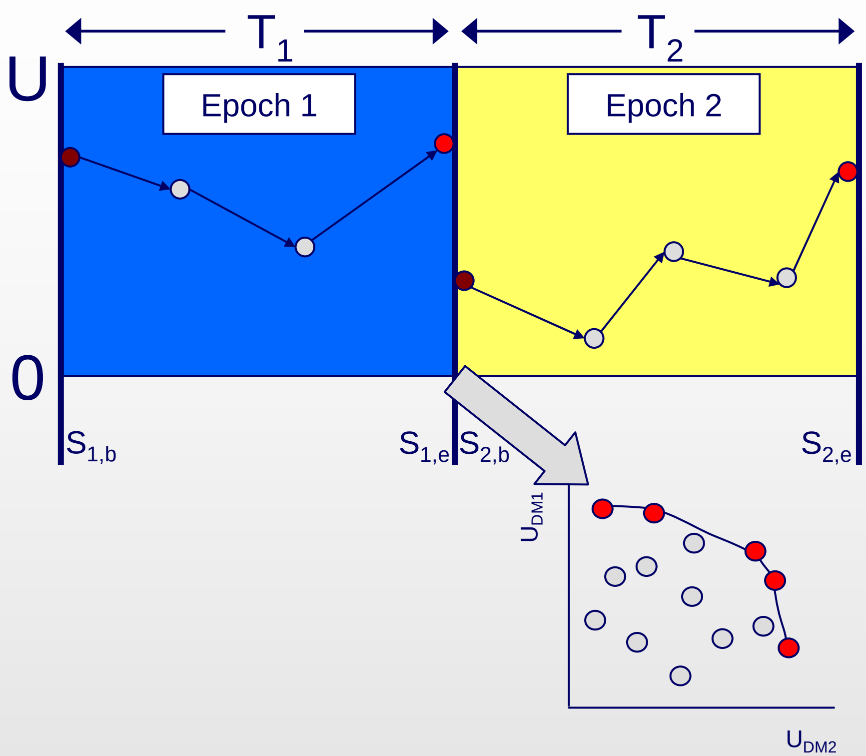
Example Scenario: Two Epochs



Epoch 1

The Status Quo

System may degrade over time

Repair may be possible

Goal: recover value at *min(cost)*

Epoch 2

Tastes change

Policy changes

Technology changes

At day 1, system same, but value discontinuity

Goal: recover value at *min(cost)*

New Customers, Changed Constraints, New Concepts

Given $S_{1,b}$	If $S_{2,b}=S_{1,e}$
Explore $S_{1,e}$	Explore $S_{2,e}$
Select $S_{1,e}$	Select $S_{2,e}$

Potential strategies: min(cost), max(value), min(time), combination…

Exercise Two

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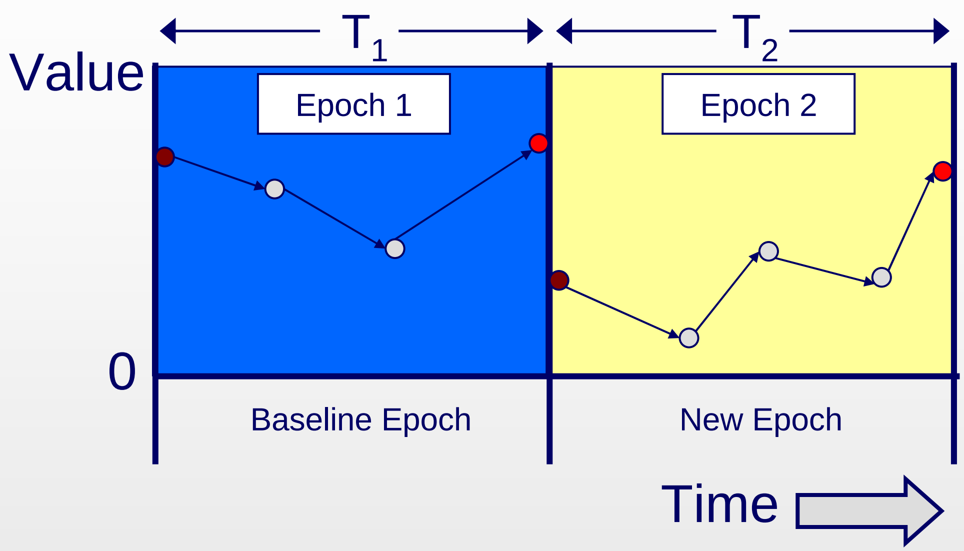

Epoch

Time period with a fixed "context"

Fixed: Constraints, concepts, available technology, and expectations (attributes and utility function)

Please see handout

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4. Performing Epoch-based Analysis

Epoch-Era Analysis

natural value-centric life cycle

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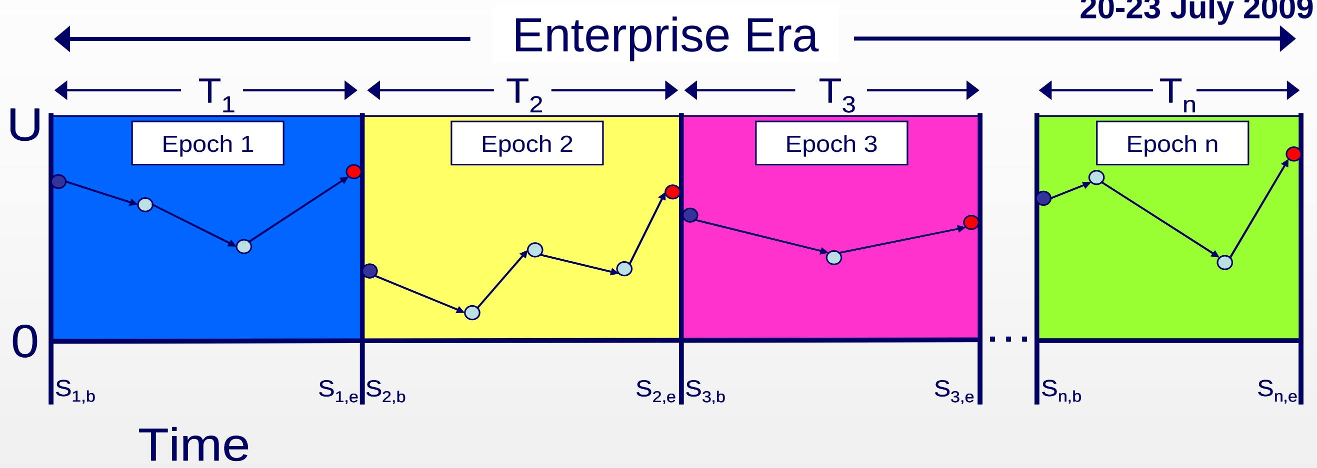
Epoch is a time period for which context and expectations are fixed



Example triggers for new epoch

- Change in political environment
- Entrance of new competitor in market
- Emergence of significant stakeholder need
- Policy mandate for privatization of enterprise

Epoch-based Analysis

design strategies to address possible futures

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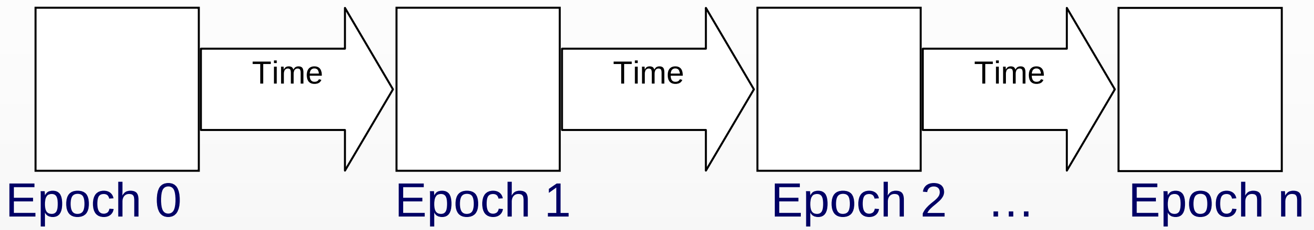

view	Architecture Change Strategies in Response to Epoch Changes
Policy/External	
Strategy	
Process	
Organization	
Knowledge	
Infrastructure	
Products	
Services	

Current approach is to develop strategies for current state to future state enterprise

….epoch-based analysis enriches this by considering strategies across anticipated epochs

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Illustration of Constructs
“Classroom” Example

Epoch-based Analysis for "Coffee Enterprise"

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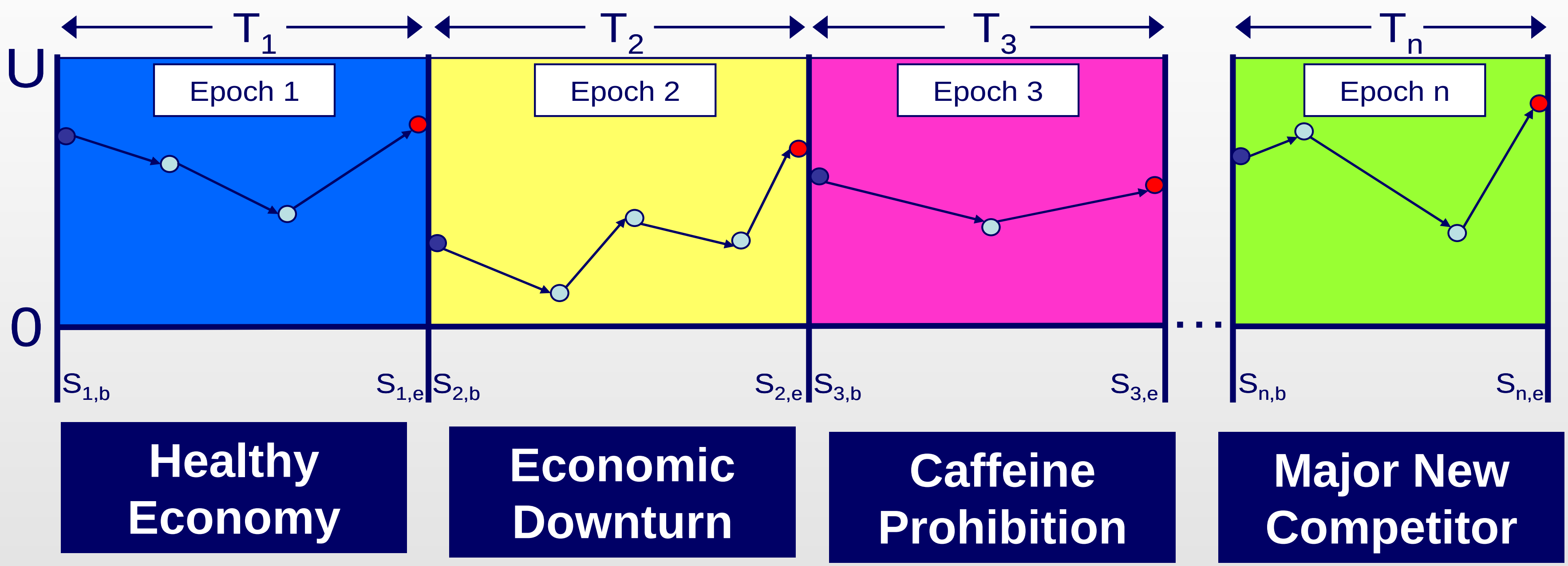
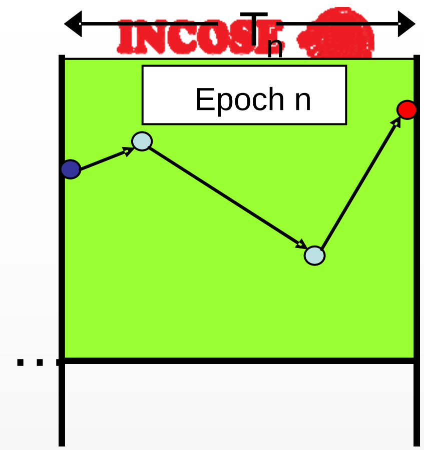


Epoch-based Analysis "Coffee Enterprise"



The Epoch Vector is composed of the selected epoch variables, which describe the full range of context uncertainties under which enterprise performance will be analyzed.

Variable Types	Epoch Variable	Examples
Strategic Factors	**Brand Coherence**	**Pricing flexibility, standard signage in stores, standard brochures**
Market Factors	**Competitor Profile**	**Competitor enters coffee market**
Policy Changes	**Product/Service Restrictions**	**Food restrictions by FDA, new labor policies limit work hours**
	Allowable Market	**Prohibited market opens**
Economic Factors	**Health of Economy**	**Downturn leading to market size change or product preference change**
Resource Change	**Investment Level**	**Corporate invests heavily in regional growth of new stores**
	Investment Profile	**Corporate funds available for store expansion, test marketing, or IT**
Infrastructure	**Standardization**	**Freedom to choose local supplies, use local accounting auditors, etc.**

Coffee Enterprise Example

View	Architecture Change Strategies in Response to Epoch Changes **Healthy --- Downturn --- Prohibition --- Competitor**
Policy/External	*Invest in building regional image to strengthen brand.*
Strategy	***1. Expand licensing to areas where economic downturn has less impact (e.g., hospitals, libraries)*** ***2. Partner with companies that offer alternative products with better range of pricing and market*** ***3. Close stores in Epoch2 where ability to compete in Epoch 4 will be most difficult***
Process	*Incorporate additional criteria into store location evaluation process …*
Organization	*Strengthen capacity to move workforce across stores in hub.*
Knowledge	*Revisit core values to see these withstand the epochs….*
Information	*Centralize IT to save costs, egional adjustments to products and pricing.*
Products	*Introduce alternative products/services for lower cost*
Services	*Allocate foundation projects at regional level to downturn related causes'.*

Applying Constructs to SoS Enterprise

Examples of Epoch Variables for SoS Enterprise

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Variable Types	Epoch Variable	Examples
Market Factors	***Acquisition Paradigm***	Low incentive for interoperability Interoperability favored in acquisitions Directed SoS acquisition
Policy Factors	***Allowable Constituents***	Limitations to national enterprises Extension to cross-national enterprises
Economic Factors	***Health of Economy***	Healthy economy with aggressive investment Downturn with investment cutbacks

Characterization of Views Across SoS Enterprise Epochs (1)

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	Epoch 0 Peace-time	**Epoch 1** Net-Centric Technology	**Epoch 2** Conflict Environment
Enterprise Architecture Form	***Collection of Unconnected Systems***	***Collaborative SoS***	***Directed SoS***
Policy/ External Factors	Enterprise motivated to deliver standalone products/services	Net-centric paradigm provides means for collaboration	Threat leads to desire to control by central authority
Strategy	Enterprise delivering single systems	Enterprise collaborates with others for SoS value	Enterprise operates as formal constituent in SoS enterprise
Process	Enterprise-driven with integration to enable business goals	Focus on process interfaces and alignment	Integration of key processes across constituents
Organization	Structured to achieve local goals of enterprise	Federation model to serve both local and global goals	Integrated enterprise favoring global goals as primary

Characterization of Views Across SoS Enterprise Epochs (2)

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	Epoch 0 Peace-time	**Epoch 1** Net-Centric Technology	**Epoch 2** Conflict Environment
Enterprise Architecture Form	***Collection of Unconnected Systems***	***Collaborative SoS***	***Directed SoS***
Knowledge	Knowledge sharing within the enterprise	Open sharing or per agreement between constituent enterprises	Control of knowledge at SoS enterprise level
Infrastructure	Local infrastructure	Local infrastructures with loose coupling between enterprises	Commonality across infrastructure with tight coupling
Products/ Services	Responsive to market forces and/or procurer requests	Responsive to pull from stakeholders and push from constituents	Responsive to direction from central authority

Architect's challenge is to look for architectural strategies to address the anticipated epochs across enterprise lifespan

Era Construction

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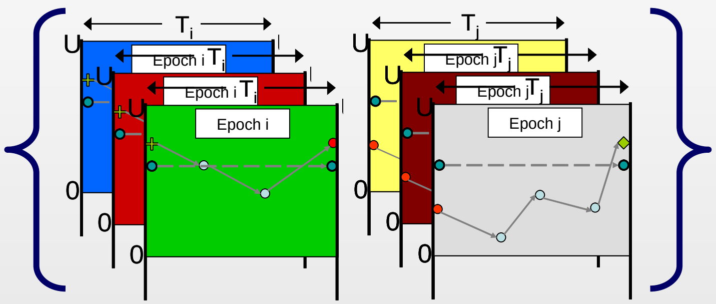
Definition of Era:

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

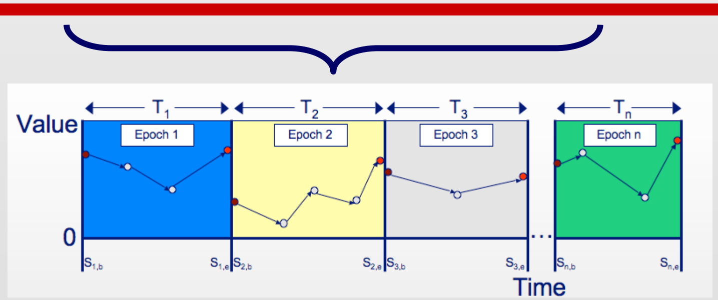
Define Epochs

- Potential Contexts
- Potential Needs



Construct Eras

- Epoch Series
- Dynamic Strategies



Discretization of change timeline into short-run and long-run enables analysis. Allows evaluation of system varying performance over possible futures or scenarios

Using Eras to Generate System Evolution Strategies

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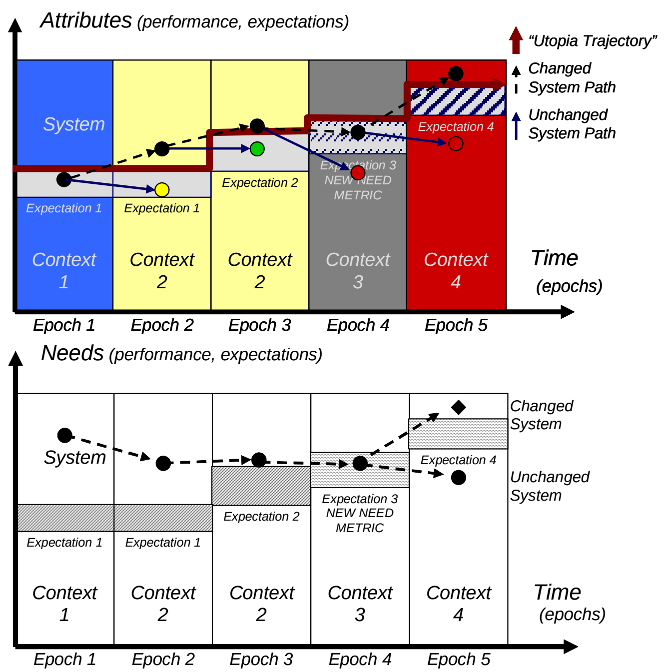
Develop time-based strategy for selecting designs that continue to deliver value to stakeholders across epochs

- Relevant metric: Minimized distance from "Utopia trajectory" of a system's performance in a given strategy



Trajectories across a system ***Era*** can be defined:

1. Set of expected Epochs
2. Strategy for selecting designs in each Epoch (e.g. min cost, max utility, etc.)

Multiple Eras defined and system selection strategies compared to "Utopia trajectory"

Exercise Three

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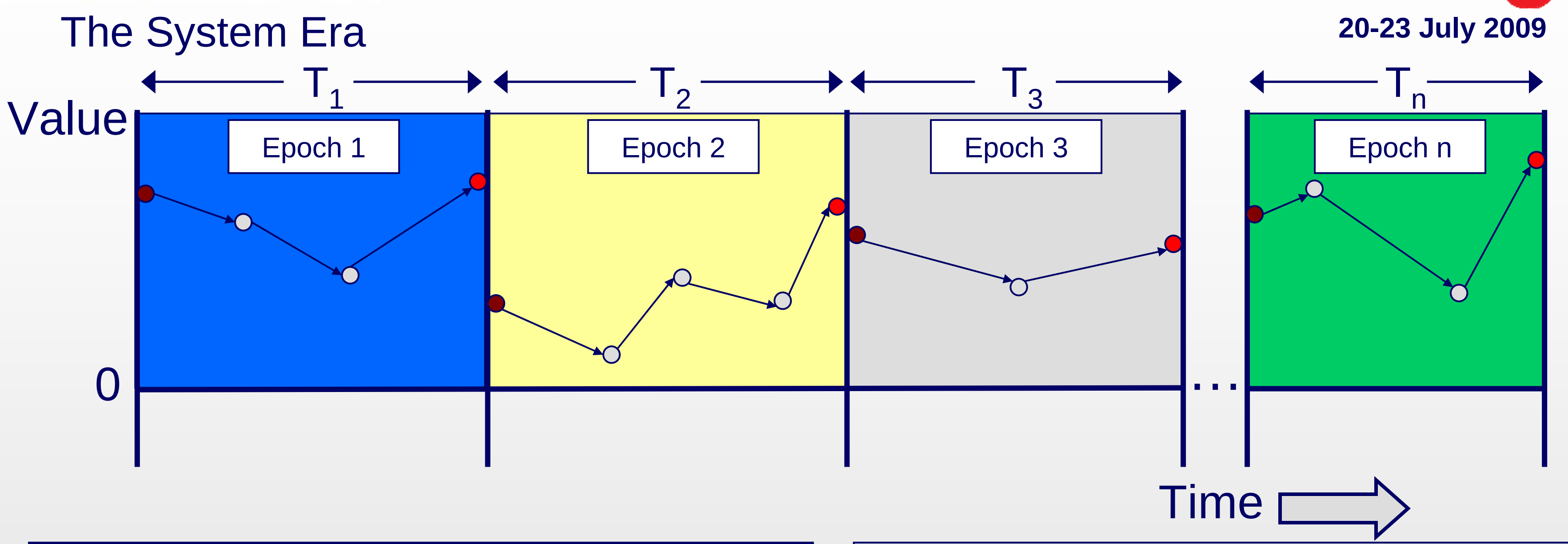

Epoch

Time period with a fixed "context"

Fixed: Constraints, design concepts, available technology, and expectations (attributes and utility function)

Epoch Purpose

Partition problem into series of short run problems

T_i: Duration of Epoch i

One Epoch: short run
Multiple Epochs (System Era): long run

Please see handout

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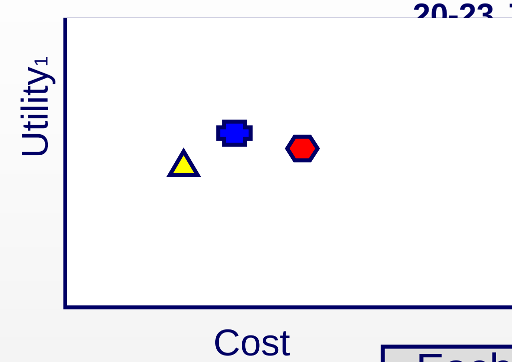
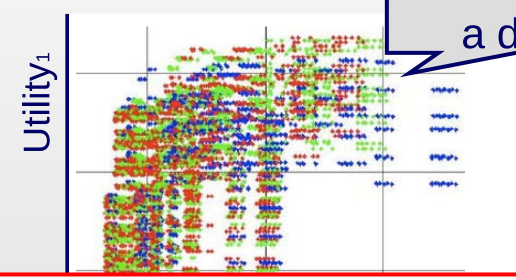
5. Overview of Advanced Approach

Background

- Traditional SE
  - Cost As Independent Variable
  - Few Design Points
  - Trades/patterns not clear

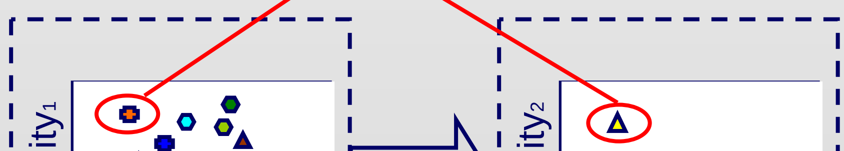


- Multi-Attribute Tradespace Exploration (MATE)
  - Parametric exploration
  - Thousands of designs



"Best" design may change over time

- Dynamic MATE
  - Tradespaces over time



What are the factors that cause the "best" design to change over time?

How does one choose the "best" design?

 (Ross and Hastings 2005, Ross 2006)

Scenario Planning

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- Scenario planning refers to a broad set of methods used to make strategic decisions

	Narrative	**Computational**
Description	Thickly-descriptive, Internally consistent	Parametric enumeration of future contexts
Pros	Compelling, more detail, plausible	Many futures, surface counterfactuals
Cons	Few future contexts considered	Computationally intensive

- Differing degrees of automation in computational scenario generation
  - Morphological
  - Expert systems

Scenario planning allows strategic management of uncertain contexts

Epoch-Era Analysis

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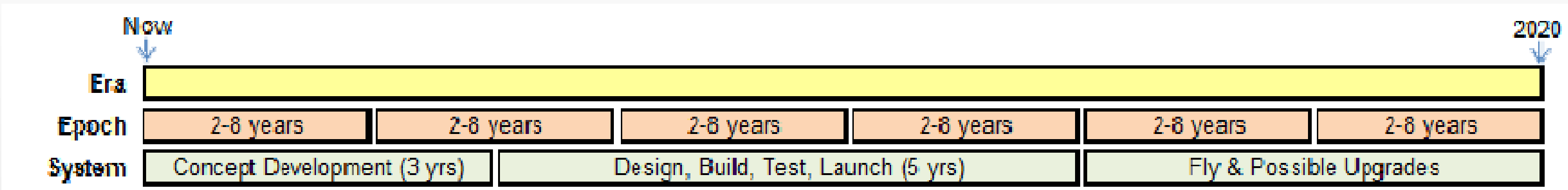
- System Development Lifecycle (SDLC) is a crucial organizing construct for managing system design activities, but does not facilitate management of uncertain contexts



(Ross and Rhodes 2008)

- Epoch
  – A period of time during which the context is static
  – Duration is determined by underlying dynamics of contextual factors considered
- Era
  – Spans the total lifecycle of a system
  – Constitutes an integrated set of epochs
  – Allows analysis of system evolution strategies

Epoch-Era Analysis provides a structured way to consider impact of context changes over the SDLC

Case Application: Satellite Radar (SR)

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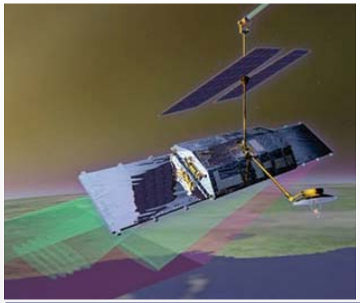
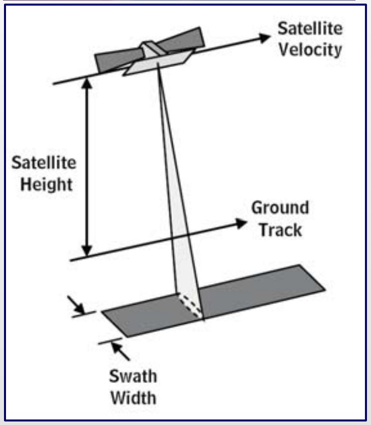
- Critical issue in national security space
  - Unique all-weather surveillance capability
  - Opportunity for impact given ongoing studies
  - Rich multi-dimensional tradespace
- Unit-of-analysis: SR architecture
  - Radar payload
  - Constellation of satellites
  - Communications network
- Articulated ***need*** for rigorous ***front-end systems engineering***
  - Uncertainties in future technology development, cost estimates, stakeholder needs, supporting infrastructures, and operational environments





(CBO 2007)

Case Application Goal

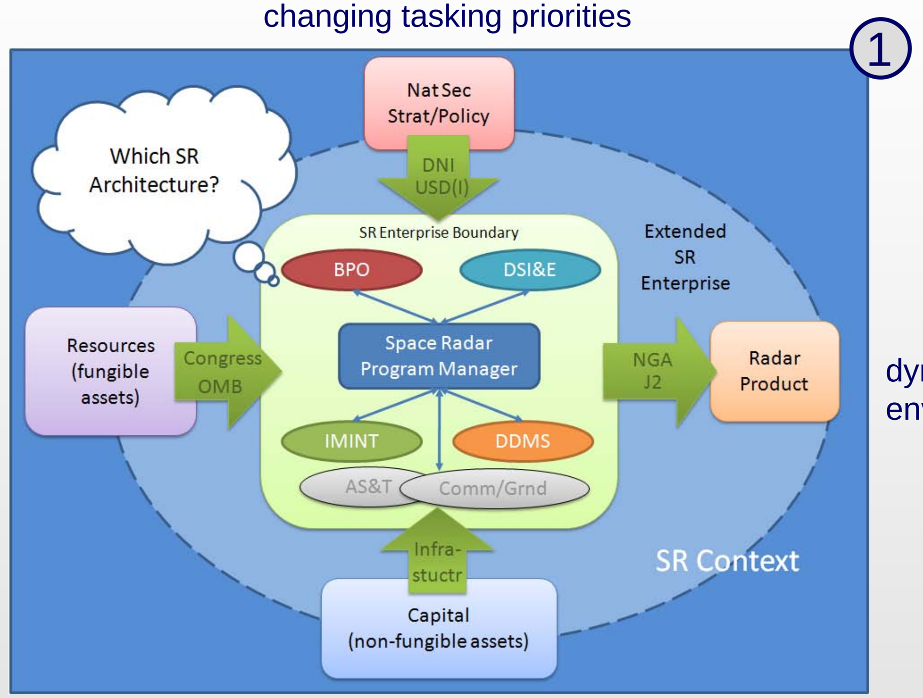
*To assess potential **satellite radar** architectures for providing the United States Military a global, all-weather, on-demand capability to **track moving ground targets**; supporting tactical military operations; maximizing cost-effectiveness; and **delivering value despite changes in context**.*

Step 1: Characterize Key Exogenous Uncertainties

- Satellite Radar provides rich problem for dynamic tradespace methodology
- Dynamics:
  - Policy
  - Funding
  - Infrastructure
  - Environment

DoD/IC stakeholders
changing tasking priorities

funding instability



dynamic environment

uncertain technology availability
uncertain ground/relay infrastructure

(Ross et al 2008)

Given distribution of future uncertainties, how does satellite radar program manager select the "best" architecture?

Parameterizing Contexts: Epoch Variables

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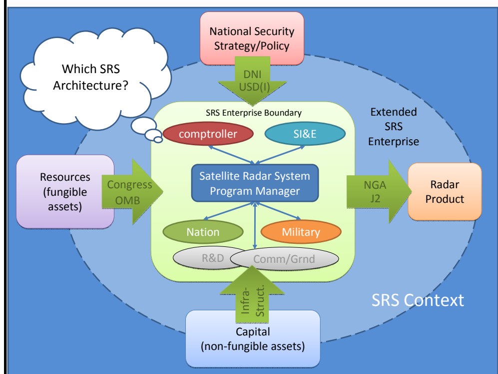

Enterprise scoping exercise informed the types of "epoch variables" encountered by program

– Enumerate hundreds of contexts
– Analogous to design variables

Epoch Vector

Category	Variable Name	Definition	Range
Capital	**Technology Level**	Includes constants for spacecraft (ex. radar and bus) available technology	**Level 1 (Low),** equiv. TRL = 9 technology **Level 2 (High),** equiv. TRL = 4 technology
	Comm. Level	Availability of ground stations and space-based relay options	**Level 1** – No Backbone + AFSCN Ground Sites **Level 2** – WGS + AFSCN Ground Sites
	AISR	Availability of AISR assets	Yes / No
Radar Product	**Target list**	Defines the target areas of interest along with target RCS variations	**Op plan 9:** Venezuela: small and N .Korea: small **Op plan 19:** Venezuela: medium and Russia: small **Op plan 44:** Iran: small and Russia: large **Op plan 45:** Iran: small and N. Korea: small **Op plan 49:** Iran: small and China: medium **Op plan 60:** Iran: medium and China: large **Op plan 84**: Russia: medium and China: large **Op plan 94:** N. Korea: small and China: medium **Op plan 103:** China: small and China: medium
	Environment	Communications jamming	Yes / No
Nat Sec Strat/Policy	***Utility SAR v. GMTI***	Relative importance of the two stakeholder types of multi-attribute utility	**Level 1** – SAR < GMTI **Level 2** – SAR = GMTI **Level 3** – SAR > GMTI
Resources	***NA***	Vary budget constraints	Era-level Attributes

648 Future Contexts

Epoch variables allow for parameterization of some "context" drivers for system value

Step 2: Epoch Enumeration

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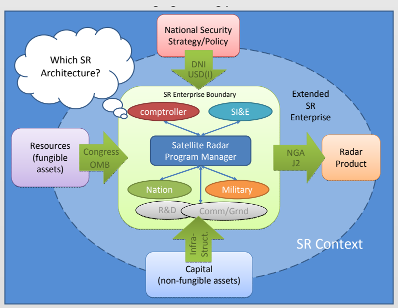
- Characterize plausible future context states (epochs)
- Initial set of 14 epoch variables identified
- QFD-like analysis led to a reduced set of 6 epoch variables
- Characterize levels for each variable
- Enumerate epochs to form the epoch sample space

①



② Example of Two Epoch Variables

Exogenous Variable Category	Epoch Variables	Enumerated Range	Units/Notes
Capital	Technology Readiness Level – Radar Aperture	[1,2,3]	1=Small aperture 2=Med. aperture 3=Large aperture
Capital	Communication Infrastructure	[1,2]	1= Legacy comm. 2=Wideband comm.

Epoch Set

648 Total Epochs

Tradespace Exploration

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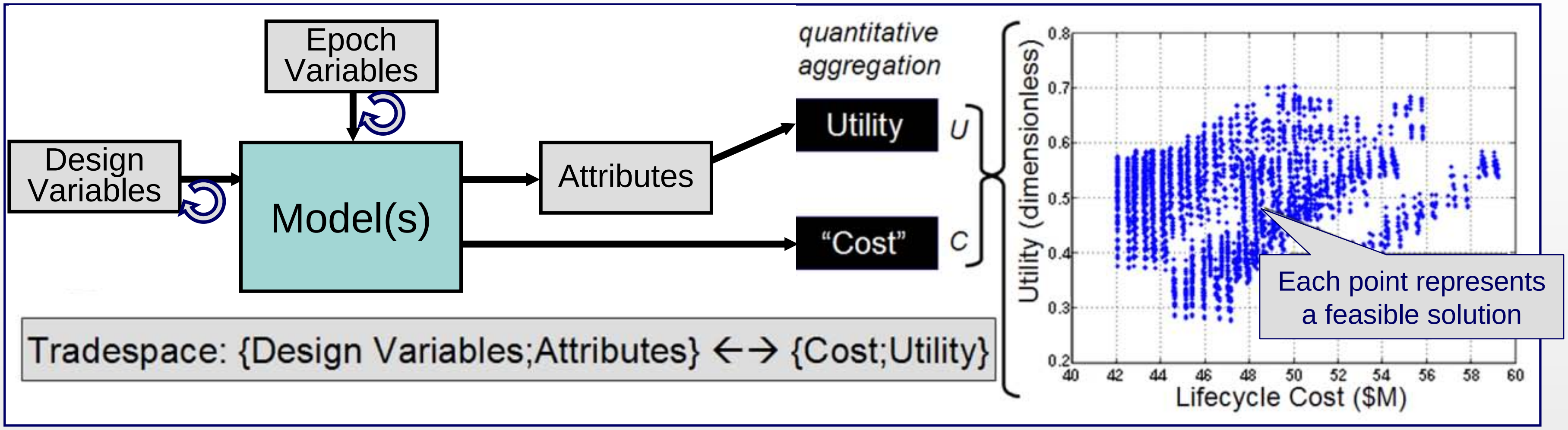


Compares many designs on a common, quantitative basis

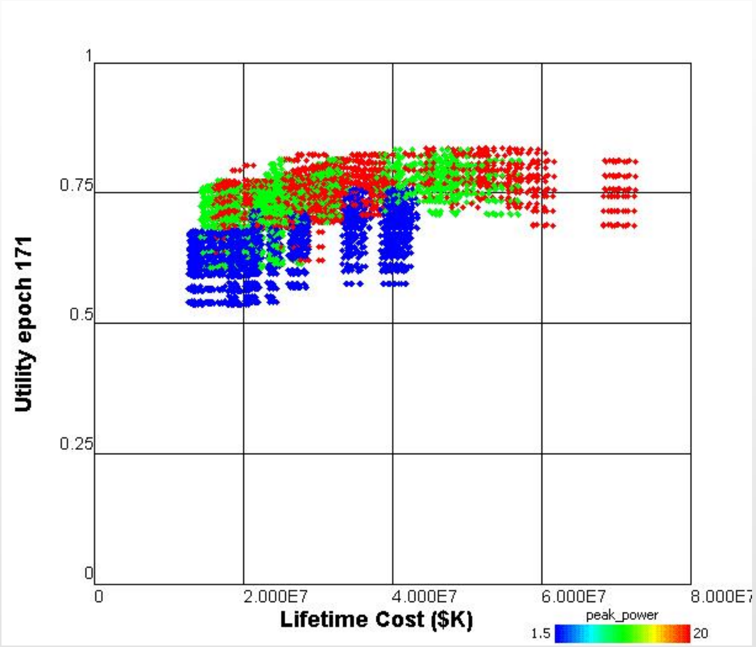
- Maps structure of design space onto stakeholder value (attributes)
- Uses computer-based models to assess thousands of designs, avoiding limits of local point solutions
- Simulation can be used to account for design uncertainties (*e.g.*, cost, schedule, performance uncertainty)

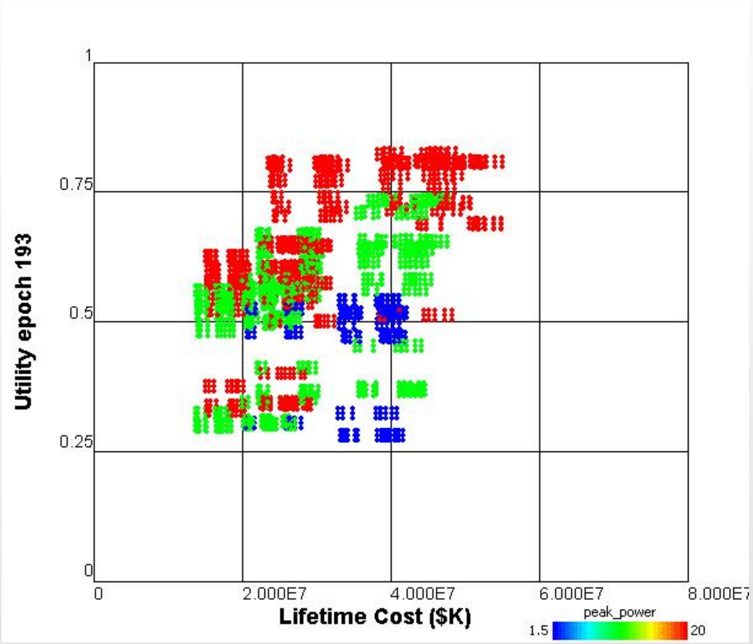
Typical goal: maximize aggregate benefit (utility) and minimize aggregate cost (lifecycle cost)

Design tradespaces provide high-level insights into system-level trade-offs

Impact of Changing Contexts

Epoch "171"	Epoch "193"
Baseline Program Context: Standalone capability needed, Imaging mission (primary)	**New Program Context:** Cooperative capability needed, Tracking mission (primary)





- Epoch 193 has more demanding mission and more emphasis on tracking user needs
- Color shows Radar peak power
- Tradespace sparser: more alternatives do not meet minimum requirements
- Delighting users harder: note utility scale

Changing context and "mission" drastically changes the value of alternative systems

Step 3: Era Construction

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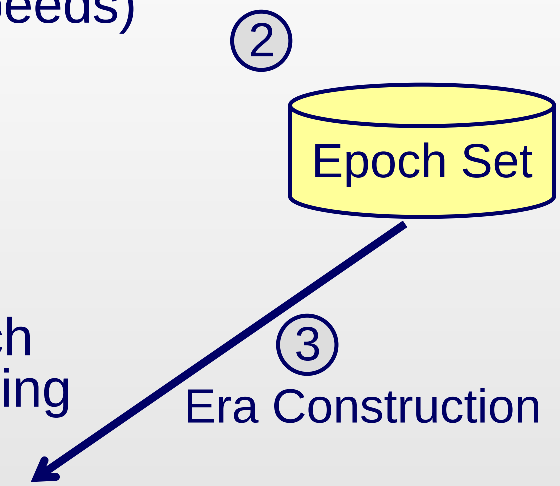
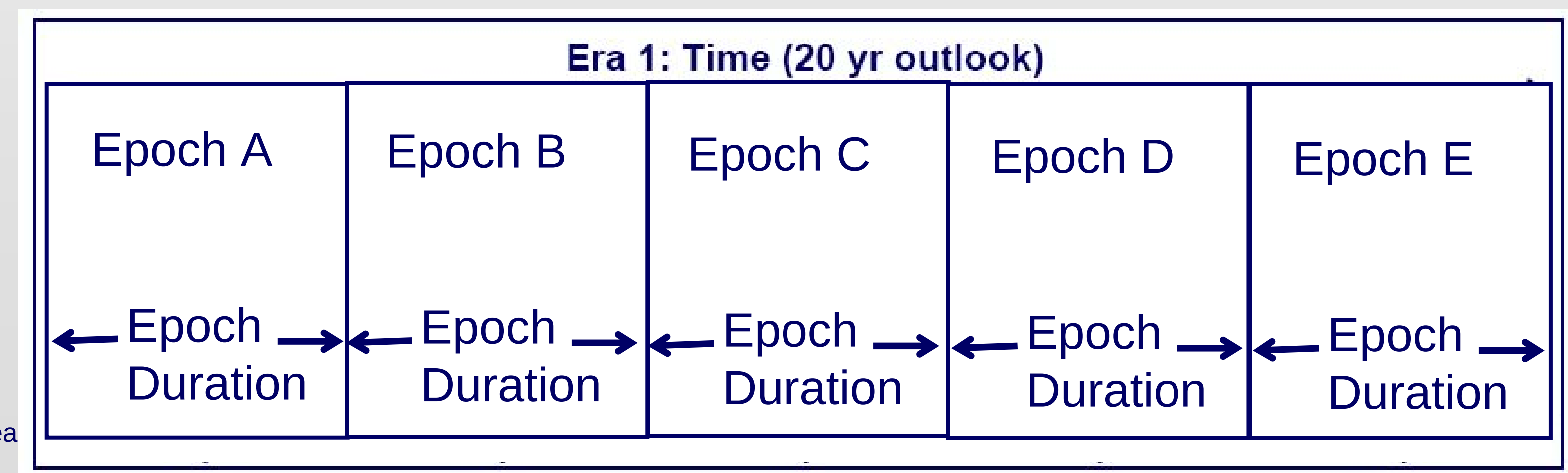
- Era construction involves four activities
  - Specify era duration
  - Characterize epoch durations (clockspeeds)
  - Establish epoch ordering logic
  - Construct Eras
- Satellite Radar Case:
  - 20 year era duration
  - Morphological approach used for epoch durations, transition logic, epoch ordering
  - 7 eras analyzed





Era Construction using Scenarios

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7 Sample Era Scenarios

- **Eras 1 - 3:**
  Emphasize shift from imaging mission to tracking mission;
  Modeled after real world historical scenario
- **Eras 4 & 5:**
  Focus on evaluation of advanced technology across strained operations
- **Era 6:**
  Evaluate importance of infrastructure advancements
- **Era 7:**
  Major force on force conflict

Mobile Missile Scenario

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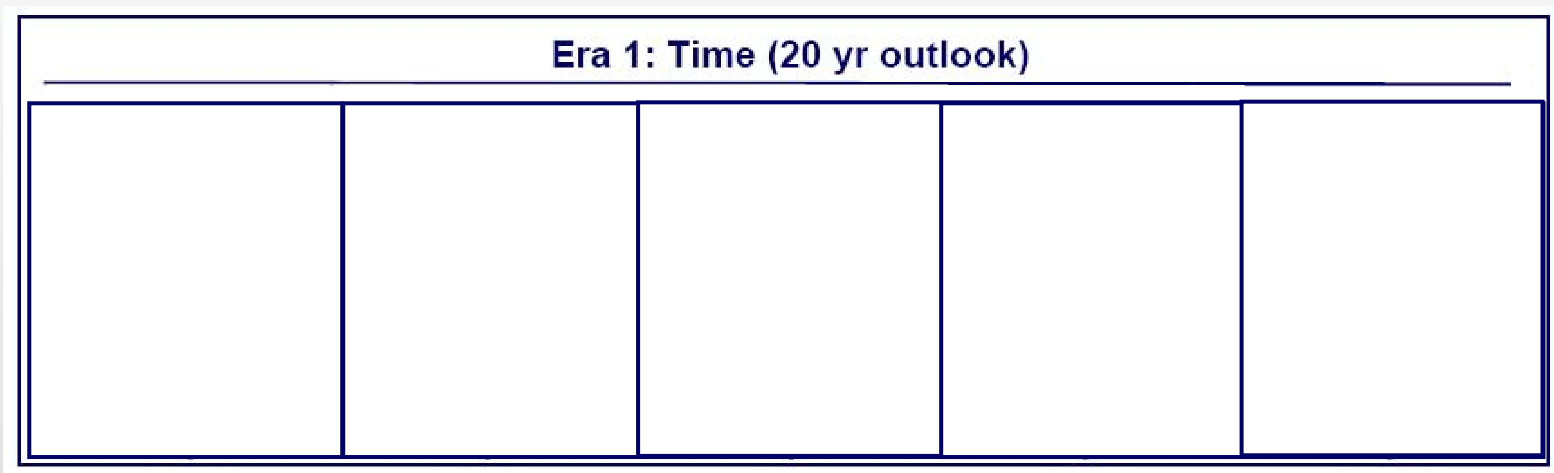
- Epoch-Era Analysis with Multi-Attribute Tradespace Exploration enables the evaluation of system value delivery through changing contexts



- Design Point 3435 (arrow) retains value despite changing context

Using Eras to Evaluate System Evolution Strategies

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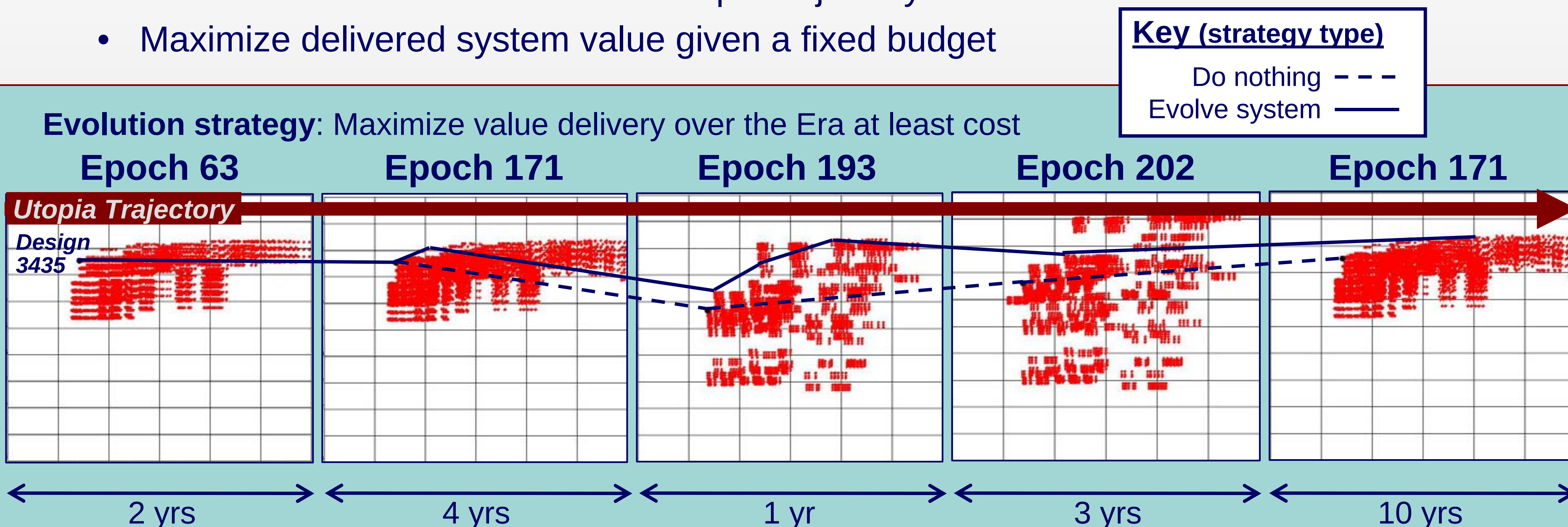
Utilize optimization approaches to derive time-based system evolution strategies that sustain / maximize stakeholder value delivery

Example strategies include:

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

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



Epoch-Era Analysis can be used to determine system designs and transition strategies that deliver the highest value over the entire system lifecycle or within a particular context

Implications

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- 2007 Congressional Budget Office study assessed 4 satellite radar system design alternatives
  - Assumed two communication infrastructures
  - Equivalent to two discrete epochs
  - No consideration of system performance across changing contexts (eras)

- Our method assessed 23,328 system designs in each of 245 epochs
  - Independent ordering of the contexts

- 7 Eras were constructed, enabling evaluation of systems across context changes
  - Important feature for path dependent system strategies

This method reveals more information about complex socio-technical interactions, enabling decision makers to better assess design choices

6. Benefits and Opportunities for Epoch-based Analysis

Linking Analysts and Architects

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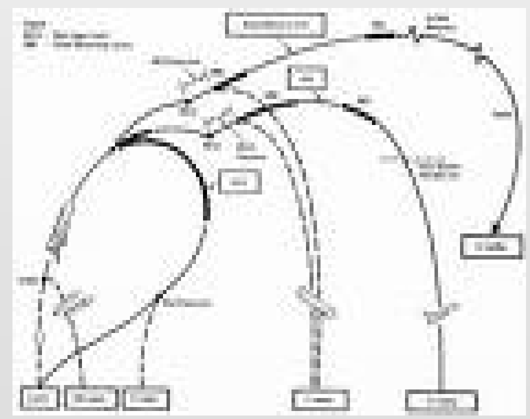
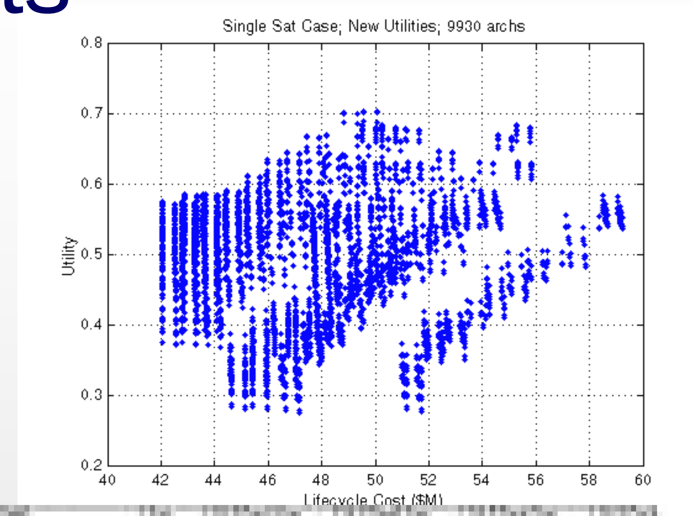
WHAT ARCHITECTS DO

- Conceptual level through use of 'storyboarding' to define high-level scenarios
- Typically performed by system architects for purpose of defining system concepts and communicating with stakeholders in an effort to learn more about their needs, expectations, and preferences
- Outcome is usually a set of "cartoon-like" graphics, and narrative operational concepts or scenario descriptions

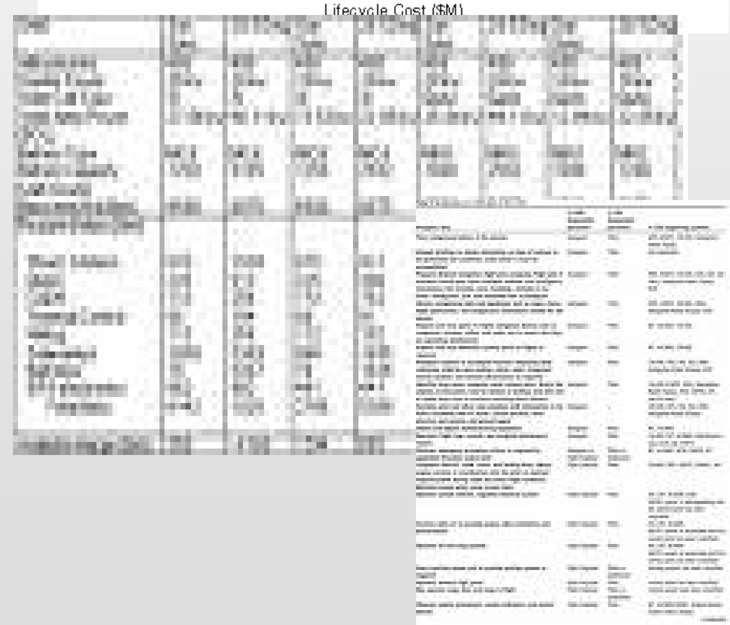


Linking Analysts and Architects



WHAT ANALYSTS DO

- Use deep analytic methods, usually modeling and simulation based.
- Activity is performed by technical specialists and analysts – often in separate organizational group
- Outcome in the form of a model and/or a highly technical report



Linking the Two

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- Shortfall of current approaches is that activities are for most part independent, focusing on two distinct aspects of the design
- Decoupled, these separate approaches miss the opportunities for informing architectural and design choices of mutual benefit.
- Leadership interventions may be necessary:
  - Planning for integrated team activities
  - Asking the right questions in reviews
  - Use of enabling venues (e.g., concept design facilities)

Emerging methods looking for better linkage…
Epoch-Era Analysis is a boundary spanning activity for dynamic tradespace exploration practice

Boundary Spanning Activity

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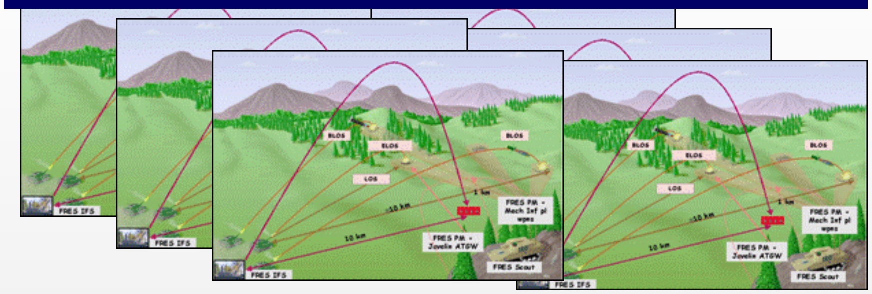
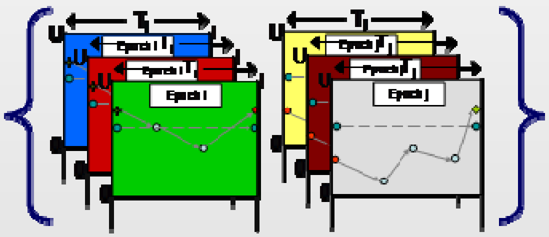
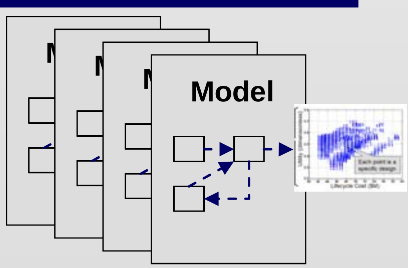
Possible Scenarios and Trajectories



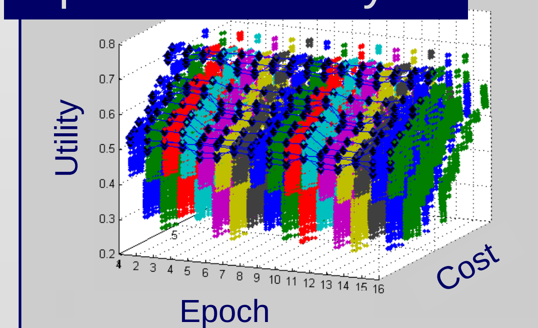
Possible Epochs and Eras



System models



Epoch-Era Analysis



- Architect develops possible "scenarios" and "system trajectories"
- Working with analyst, enumerates epochs and eras
- Analyst uses epochs to develop context-dependent models for tradespace exploration
- Software used to generate visualizations and analytically based system trajectories
- Results incorporate perspectives of architects, analysts, and stakeholders

Facilitates discussion and insight

Calculating Pareto Trace to Uncover Value Robust Designs

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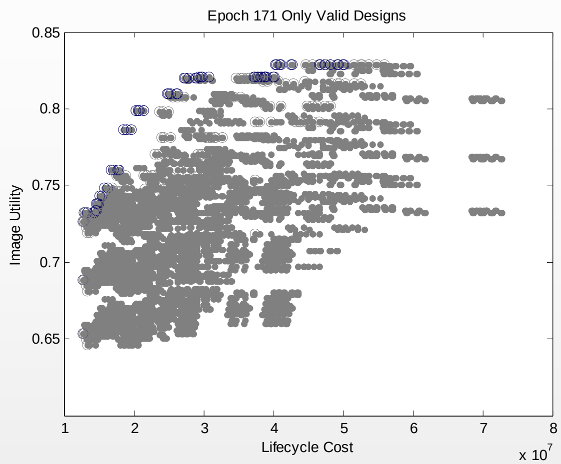
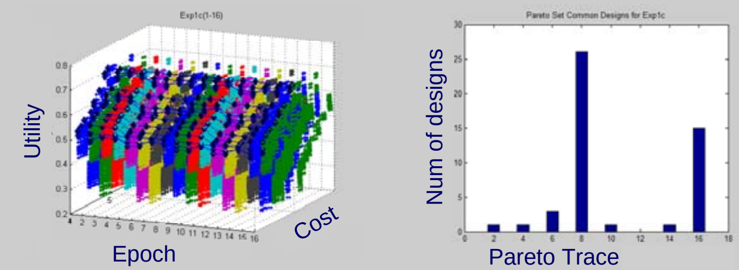


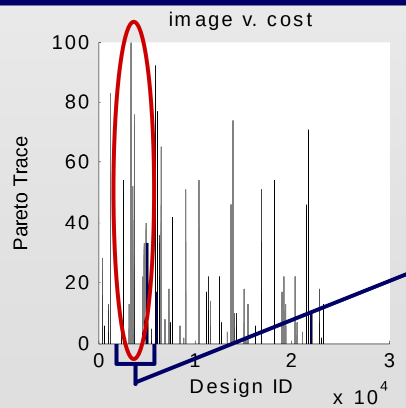
Find non-dominated solutions within a given epoch (Pareto Set)

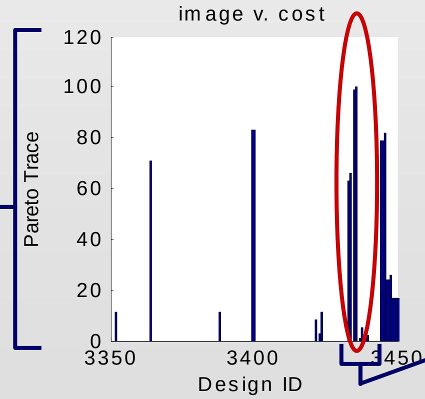
Pareto Trace

Pareto Sets containing design
(measure of passive robustness)



Across many epochs, track number of times solution appears in Pareto Set





Identify designs with high Pareto Trace for further investigation

e.g. "design 3435" is in 67% of Pareto Sets

Higher Pareto Trace designs are more passively value robust

Performing Pareto Tracing

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Perform anticipatory exploration of possible preference permutations

- Answering “what if” questions on needs…
  - What if you don’t elicit the “right” attribute priorities?
  - What if you don’t elicit all of the “right” attributes?
  - What if you don’t elicit the “right” utility curve shape?
  - What if you don’t use the “right” utility aggregating function?
  - What if a second decision maker enters the mix?
  - …
- Find designs common in Pareto Sets across varying “needs” and “contexts” epochs

Pareto Trace is a metric of passive value robustness across epoch variations

But what does absolute Pareto Trace mean, and what about designs that are “close” to the Pareto Front? Aren’t these “good” also?

Example Metrics for Epoch-Based Analysis

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For Multi-Epoch Tradespace Exploration…

Three metrics for passive value robustness

- Pareto Trace (PT)
  - # Pareto Sets across epochs in which design is considered "best"
- Normalized Pareto Trace (NPT)
  - Fraction of epochs in which design is considered "best"
- Fuzzy Normalized Pareto Trace (FNPT)
  - Fraction of epochs in which design is considered "good"

These metrics can be used to quickly identify designs and strategies that maintain value across changing contexts over time

But Passive value robustness is only part of the story…

Additional research addresses active value robustness and developing system evolution strategies…

Achieving Value Robustness

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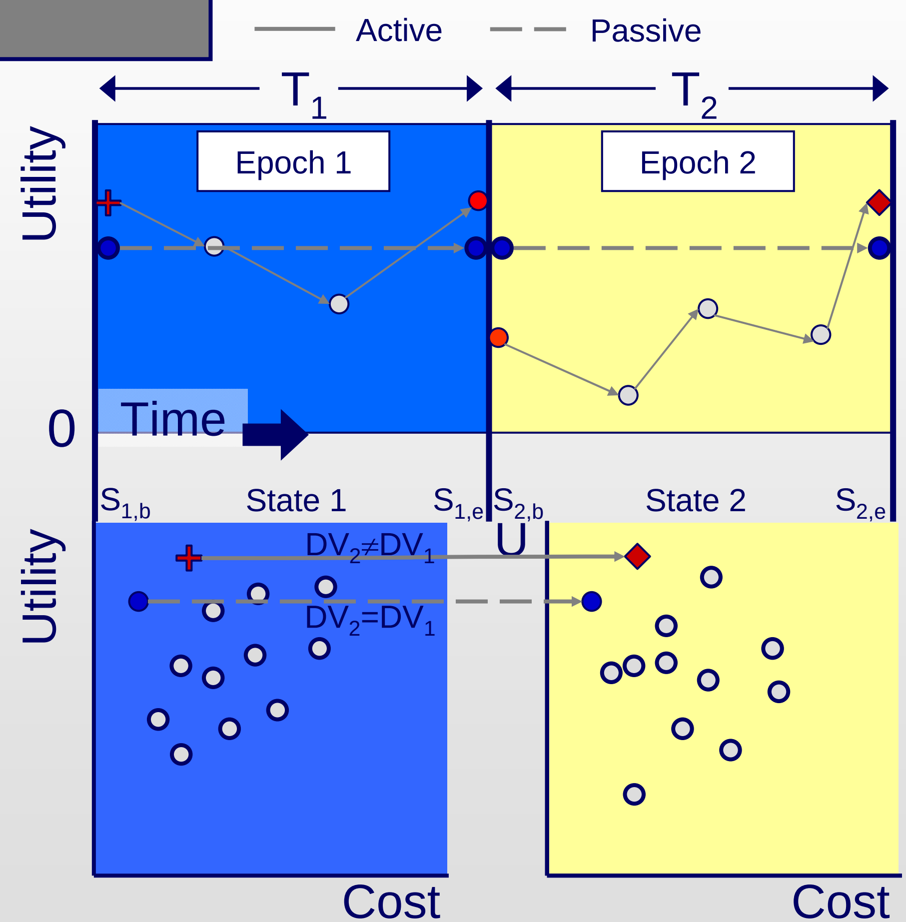
Research suggests two strategies for "Value Robustness"

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

Epoch Usage Considerations

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- An "Epoch" is a mechanism for stringing together short run (Epochs) into long run (Era), simplifying dynamic analysis
- Epochs are defined by system-external "context" changes; timescales are "natural"
- Epochs can be known in advance, or in the moment, deterministic, or probabilistic
- Epoch-Era Analysis can be conducted at any point during system lifecycle, not only conceptual design
- Modularity of Epoch-Era Analysis enhances overall tradespace exploration
- Value (utility) is defined within a given Epoch
- Selection of system end state (goal) within an Epoch is dependent on strategy (min. cost, max. utility, short run vs. long run, etc.)
- System change strategies can be predictive, adaptive, or static
- Multiple strategies for achieving value robustness across an Era

Epoch-Era Analysis can be used for visual communication as well as for quantitative networked tradespace analyses

For Discussion

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- Epoch-Era Analysis to consider multiple time periods for strategic consideration
  - Consider "natural" and "artificial" time scales
  - "To-be" state should always be evolving
  - Path-dependency may prevent future states

- Give example epoch changes that have affected a specific system's success or failure.
- What fraction of potential epochs can be anticipated?
- How can programs and organizations trade long term vs. short term system strategies?

Closing Thoughts

Gaining Insights into Systems across Changing Contexts

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- Changes in static analysis assumptions should not be a post-analysis consideration (*e.g.*, "sensitivity analysis")
- Using metrics such as *Pareto Trace* with Multi-Epoch Analysis makes such considerations a central part of trade studies
- Epoch-based metrics can be used to gain insight into:
  - Differential impact on systems of non-subtle, discrete changes in
    - Expectations or needs
    - Contexts
  - Epoch-specific valuable families of solutions
  - Inclusion of "satisficing" designs (*i.e.*, slightly "suboptimal")

Metrics are most useful as indicators for further investigation
(e.g., What is "so special" about these designs? In what epochs do they perform well and why?)

Epoch-Based Thinking

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- Epoch-Era Analysis intends to introduce a "natural" value-centric tool for system alternative generation, evaluation, and communication for dynamic and changing "contexts"
- Is scalable in application, from qualitative to deeply quantitative
- Useful as boundary object between stakeholders, architects, and analysts
- Forces consideration of essential factors for system success: meeting dynamic expectations in changing contexts

Epoch-Era Analysis helps remove the "static-view" bias in current methods by making time a natural dimension for consideration

For Further Information

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- 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 AWARD**
- Ross, A.M., and Rhodes, D.H., "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 AWARD**
- Ross, A.M., McManus, H.L., Long, A., Richards, M.G., Rhodes, D.H., and Hastings, D.E., "Responsive Systems Comparison Method: Case Study in Assessing Future Designs in the Presence of Change," AIAA Space 2008, San Diego, CA, September 2008
- Roberts, C.J., Richards, M.G., Ross, A.M., Rhodes, D.H., and Hastings, D.E., "Scenario Planning in Dynamic Multi-Attribute Tradespace Exploration," 3rd Annual IEEE Systems Conference, Vancouver, Canada, March 2009. **BEST PAPER AWARD**
- Ross, A.M., McManus, H.L., Rhodes, D.H., Hastings, D.E., and Long, A.M., "Responsive Systems Comparison Method: Dynamic Insights into Designing a Satellite Radar System," AIAA Space 2009, Pasadena, CA, September 2009 (forthcoming)

SEAri Website

Systems Engineering Advancement Research Initiative

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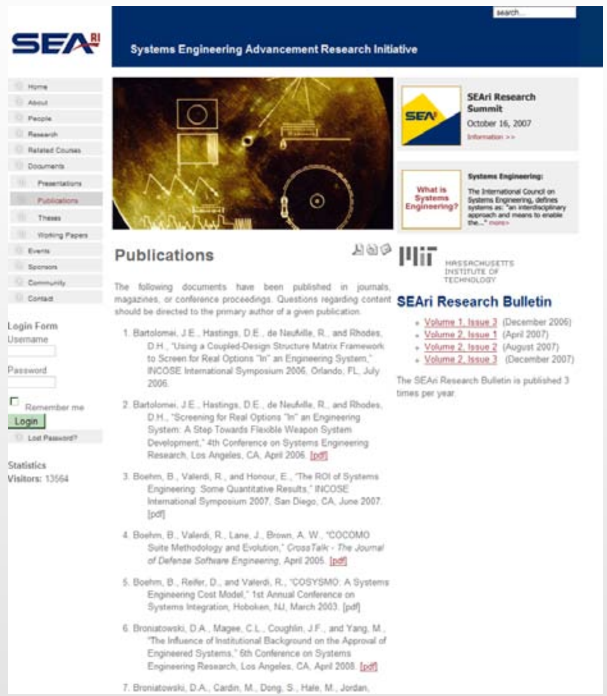

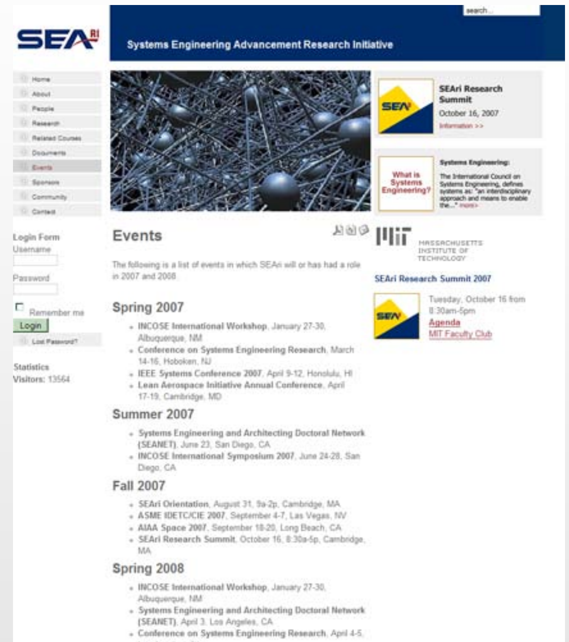

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Thank you!

Any questions?

Thoughts or suggestions? Feel free to email the authors: adamross@mit.edu and rhodes@mit.edu

Backup

Capturing Information

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- Each Epoch has specific quantities associated with it
- Definition of these quantities concretizes a given "context"
- Used as guidance for analyst-developed models

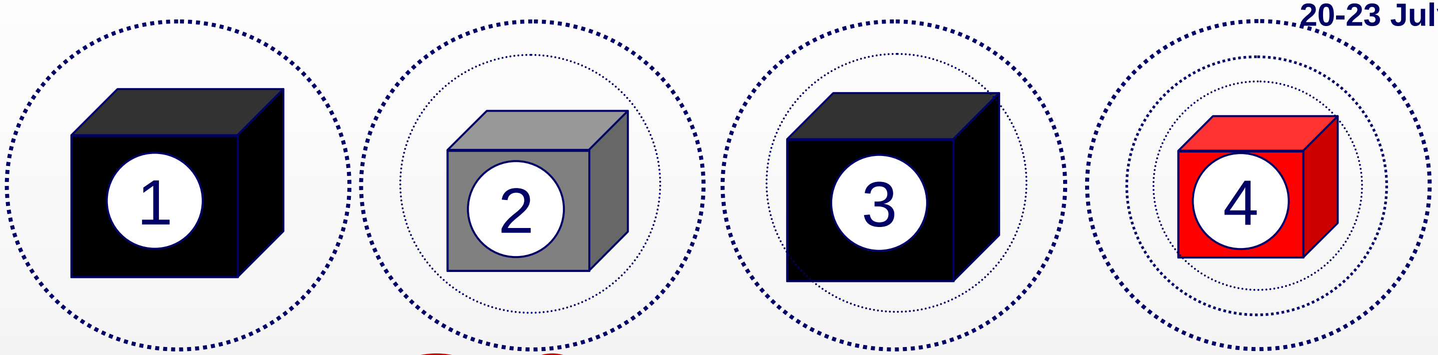
Analysis for X-TOS System Era – Epoch n	
Epoch Identifier	**Description**
Epoch Name	The descriptive name for the epoch, for example: ***X-TOS Initial Operating Scenario***
Epoch Duration	Finite duration for the epoch, for example: five years, or until system context change
Epoch Goal	Overall goal for epoch, for example: **Find Maximum Utility Design At** $S_{i,e}$
Constraints	**Description**
Resource	All of the resource related constraints including time, financial, manpower, and others, for example: *Must spend less than $100M over 5 years*
Political	The political related constraints which may be by formal policy or implicit, for example: *Must not use foreign launch vehicle*
Market	Market constraints including limitations imposed and windows of opportunity
Physical	Physical system constraints including limits by physical laws, spatial limits, etc.
Operational	The operational constraints in regard to system performance and other operating considerations, for example: *Must provide less than 5 Gbps downlink data rate*
Other	Any other constraints not enumerated in the previous categories.
Constants	**Description**
Constant Variable Set {CON}	The set of design variables that is constant within this epoch.
Controllable	The constants which are controllable by the designer.
Uncontrollable	The constants which are beyond the control of the designer.
Preference Space	**Description**
Decision Maker set, {DM}	The set of decision makers for the epoch, for example: *system user*
Number of DM {DM}	The number of decision makers for the epoch, for example 1
Attribute set, $\{X^M_i\}$:	Attribute set for the epoch, defined for each decision maker i. For example: {Data Lifespan, Latitude Diversity, Equator Time, Latency, Sample Altitude}
Attribute Priorities, $\{k^M_i\}$:	The priorities on a scale of 0 to 1, defined for each decision maker, for example: [0.3,0.125,0.175,0.1,0.425]
Single attribute utility curves, $U_j(X_j)$:	Single attribute utility curves for the epoch for each decision maker.
Multi-attribute utility curve, $f(U(k_j,U_j))$*: MAUF*	Multi-attribute utility curves for the epoch for each decision maker.
Changeability Cost threshold, $\hat{C}$:	The highest level change cost that a decision maker is willing to accept, for example $50M
Changeability Time threshold, $\hat{t}$:	Changeability acceptable time threshold of a decision maker; this varies if making decision for short term (this epoch only) or longer term (multi-epochs).
Design Space	**Description**
Design variable set, $\{DV^N\}$:	The set of design variables for the epoch, For example {Inclination, Apogee Altitude, Perigee Altitude, Communication Arch, Total DeltaV, Propulsion Type, Power Type, Antenna Gain}
Baseline design, DV_{base}:	Baseline design from the previous epoch; if this is first epoch then there is no baseline.
Path-enabling variable set, $\{IV^P\}$:	The variable set whose purpose is to enable new paths in the epoch tradespace, lowering transition cost or adding paths.
Transition rule set, $\{R^K\}$:	Rules for how to change design variable values, where change in one may result in change in another. For example, R1: Plane Change (burn on-board fuel to alter inclination), R2: Apogee Burn (burn on-board fuel to alter apogee), etc.
Cost function, F_c *(CON, DV, IV)*	The cost function for the design, based on the constants, design variables, and the path enabling variables, for example mass-based cost-estimating relationships.
Model	**Description**
Scenario	Visual and descriptive scenario, developed by Team ABC
Model(s) to be used, F_{XM}	The model(s) to be used, for example X-TOS code version 1.1 developed by Team XYZ.

Ross, A.M., and Rhodes, D.H., "Using Natural Value-centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis," INCOSE International Symposium 2008, Utrecht, the Netherlands, June 2008

Ex: Picking the "best" options

The Pursuit of Value Robustness

INCOSE 2009 SINGAPORE
20-23 July 2009



Preferences t=1

Attribute	k_i
Size	0.5
Loudness	0.2

U(3)>U(2)>U(1)>U(4)

U(4)>U(2)>U(3)>U(1)

big>small

loud>quiet

Change?

Preferences t=2

Attribute	k_i
Size	0.5
Loudness	0.2

Attribute "priority"

New

If switching costs are high, option (2) may be better choice (i.e. robust in value)

Versatile designs or changeable designs can achieve value robustness