Systems Engineering Advancement Research Initiative

Using Natural Value-Centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis

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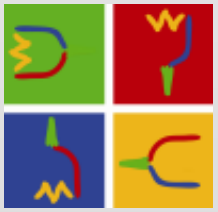
MIT

Paper Session 11, Track 1: Process 2
Thursday, June 19, 2008



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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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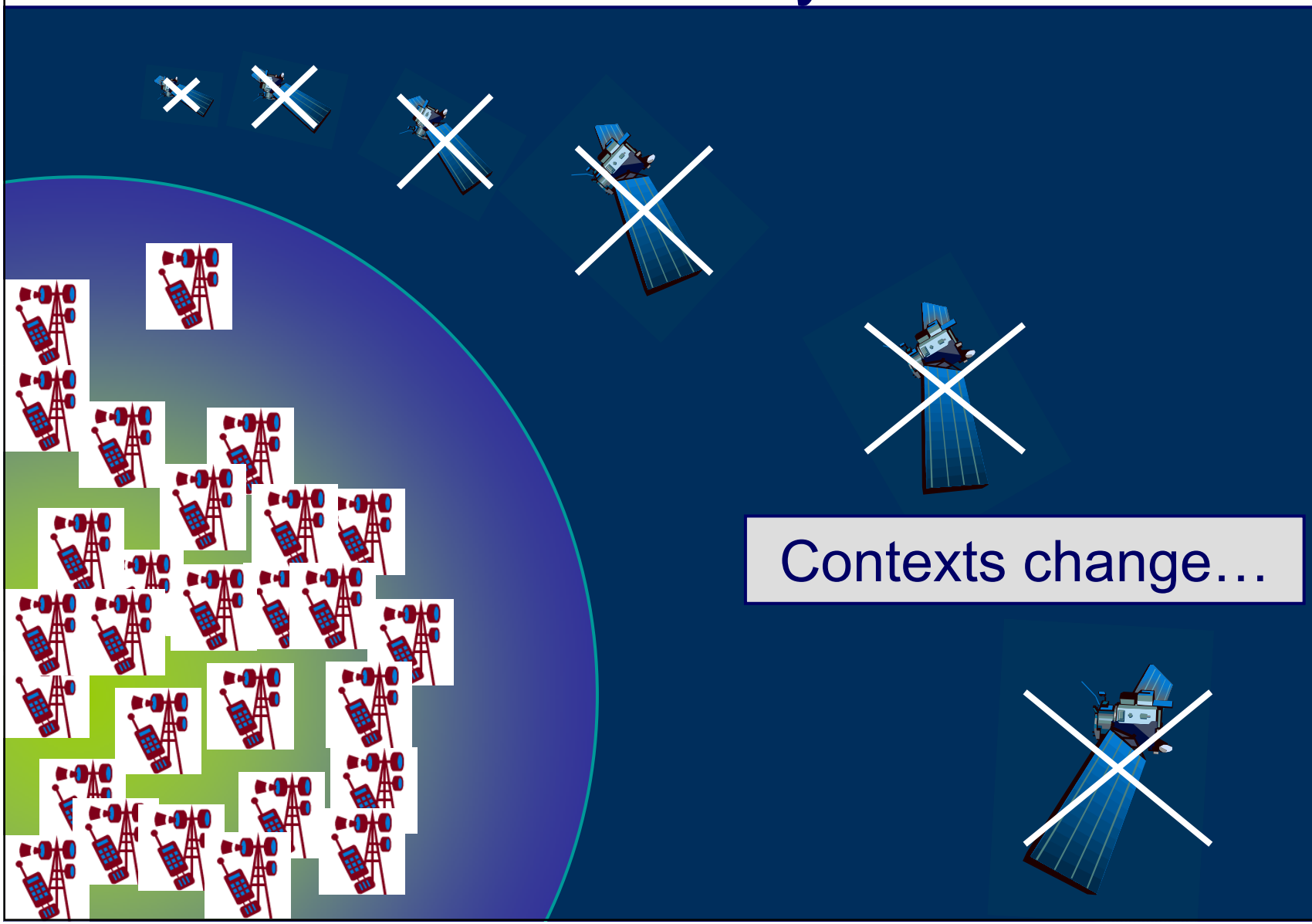
Deploying a “Valuable” System…



Meeting Customer Needs (cont.)

- Goal of design is to create value (profits, usefulness, voice of the customer, etc…)

- People change their minds; the world changes…
- To continue to deliver value, systems must cope with context change…

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What is Context?

- Context includes forces exogenous to system
  - Stakeholder expectations
  - Operating environment
  - Policy constraints
  - Available technologies
  - Competitive 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)

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What is System Success?

Success is defined as meeting or exceeding decision maker expectations

System success, Ψ

"experience" "expectations"

$$\Psi = \left[X_{DM} \geq Y_{DM} \right]$$

$$0 \leq \Psi \leq 1$$

X_{DM}	Decision maker system "experience"
Y_{DM}	Decision maker system "expectation"

Note: this is a simplistic version of a utility function (is the system attribute X above minimum acceptable level Y?)

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

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What is System Success?

Success is defined across multiple time periods

System success, Ψ, across time t

"experience" "expectations"

$$\Psi(t) = \left[X_{DM}(t) \geq Y_{DM}(t)\right]$$

$$0 \leq \Psi(t) \leq 1$$

$X_{DM}(t)$	Decision maker system "experience" at time t
$Y_{DM}(t)$	Decision maker system "expectation" at time t

Note: this is a simplistic version of a dynamic utility function (is the system attribute X(t) above minimum acceptable level Y(t)?)

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

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What is System Success?

Success is defined across multiple time periods and multiple perspectives

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

"experience" "expectations"

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

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

$X_{DMi}(t)$	Decision maker i unaffected system "experience" at time t
$Y_{DMi}(t)$	Decision maker i unaffected system "expectation" at time t

Note: this is a simplistic version of a dynamic utility function (is the system attribute X(t) above minimum acceptable level Y(t) for each decision maker?)

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

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What is System Success?

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"

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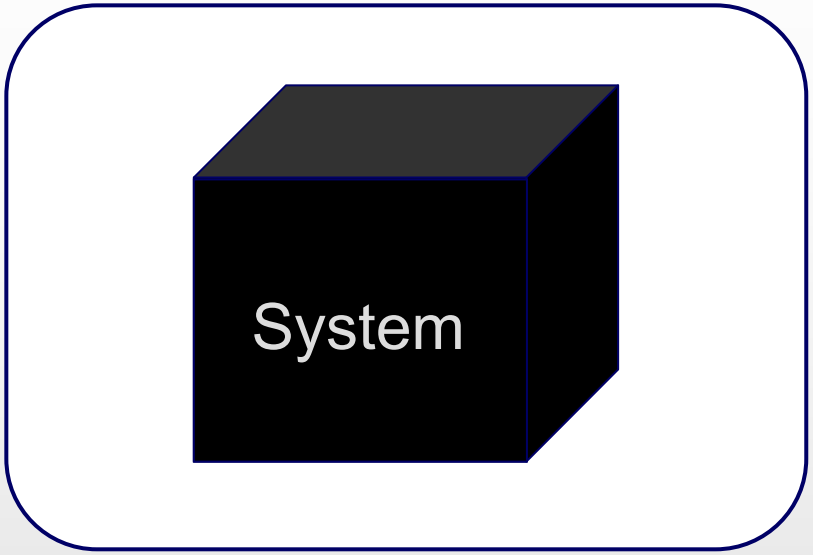
Traditional Perspective



- 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

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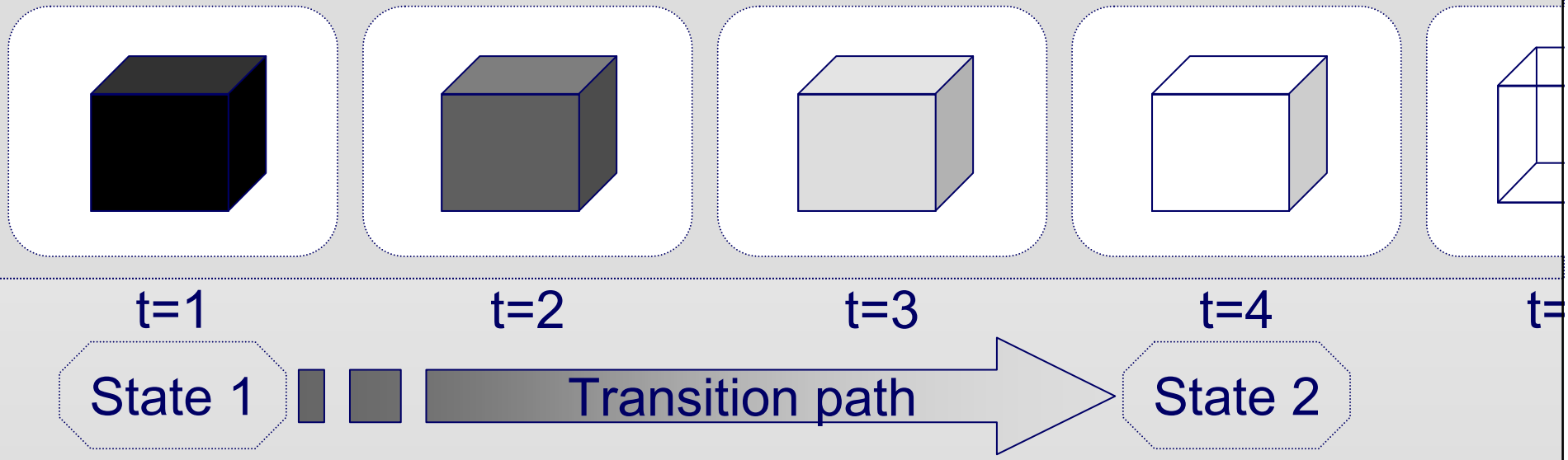
From Static to Dynamic Views

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

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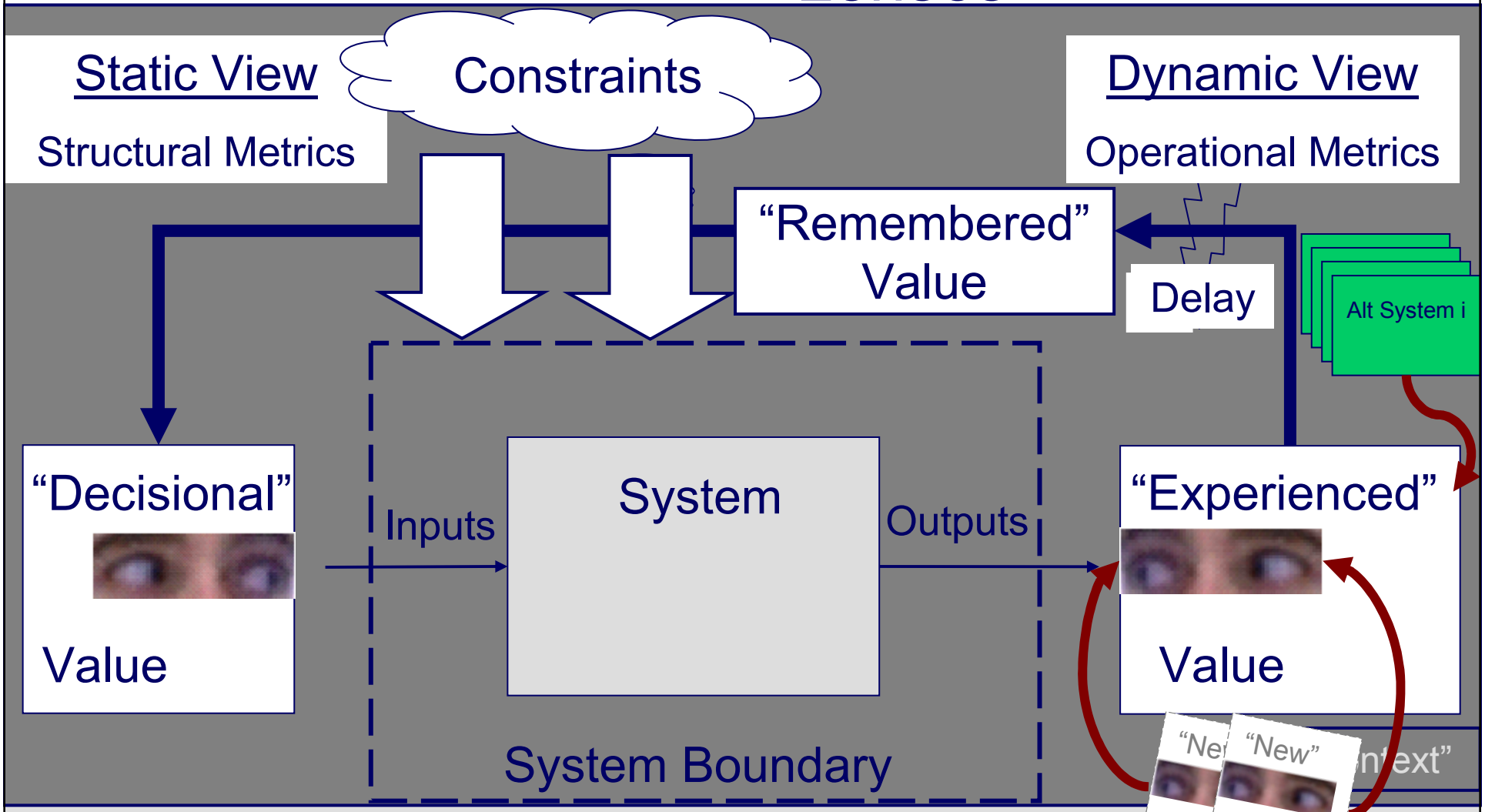
Dynamic System Context: Value Lenses



*"Decision", "Experienced", and "Remembered" Utility from (Kahneman and Tversky 2000)

**Discussion of "structural" versus "operational" metrics in (Giachetti et al. 2003)

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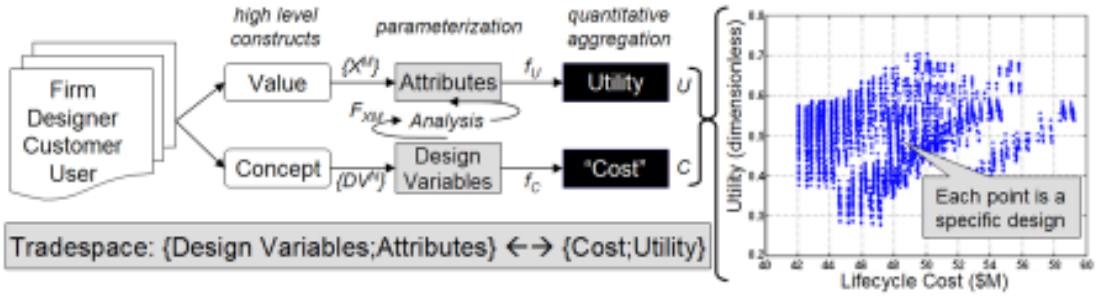
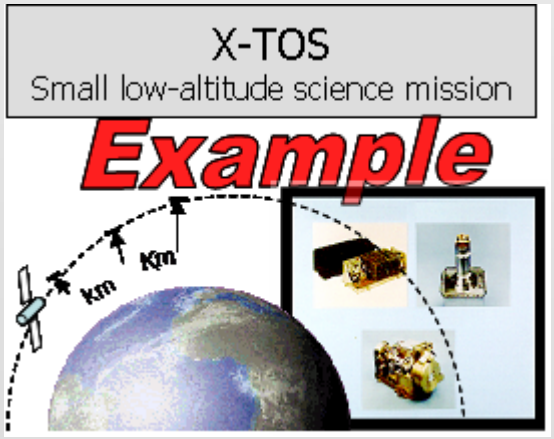
Tradespace Exploration



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

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

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



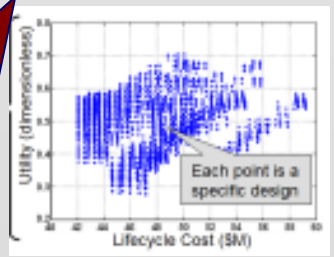
DESIGN VARIABLES:
Design trade parameters

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

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

Cost, Utility

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



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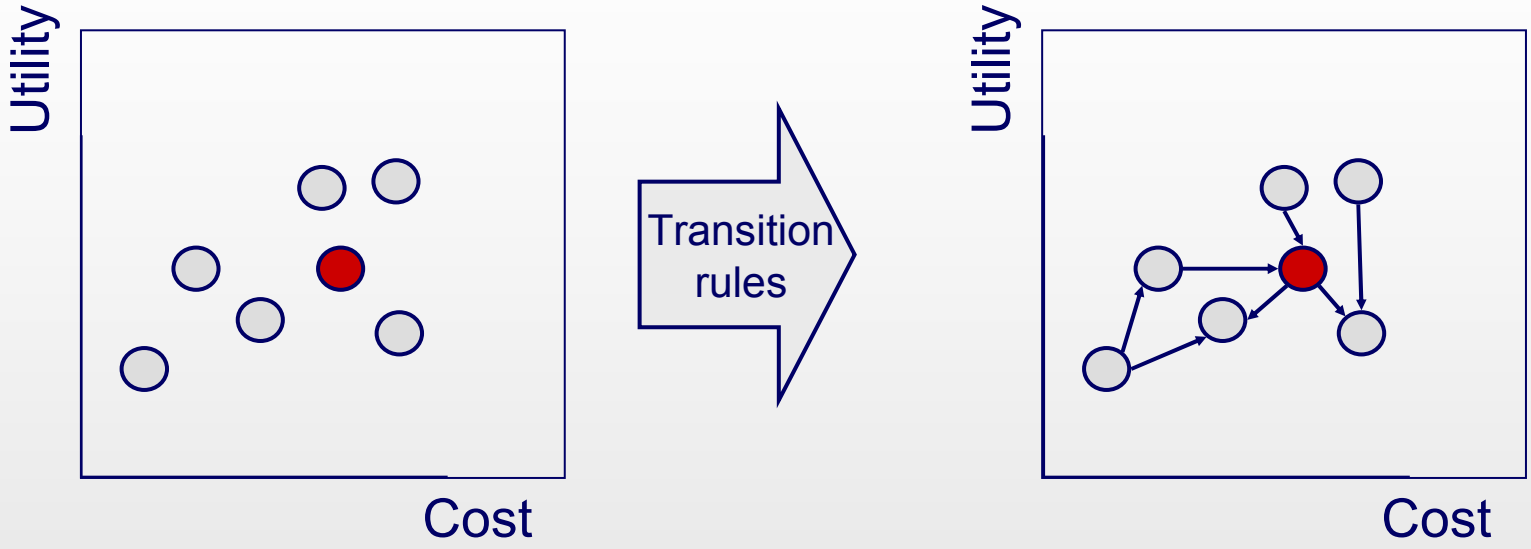
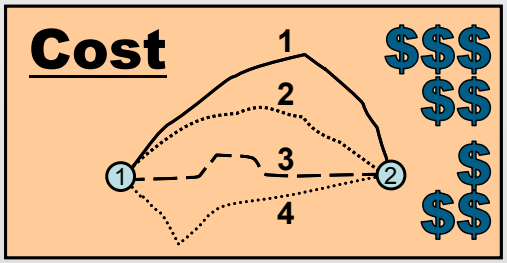
Tradespace Networks



Tradespace designs = nodes

Applied transition rules = arcs



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

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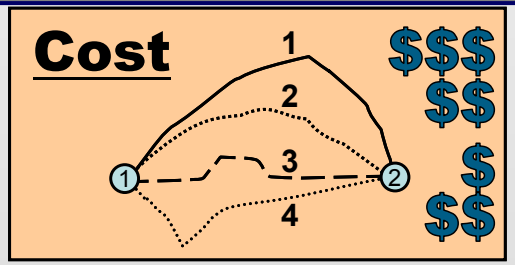
Tradespace Networks

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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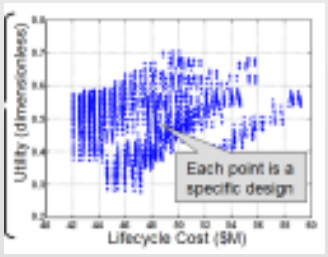
Epoch-Era Analysis



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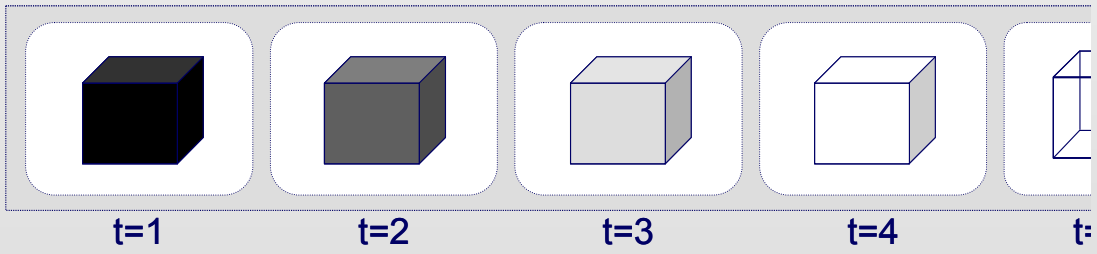

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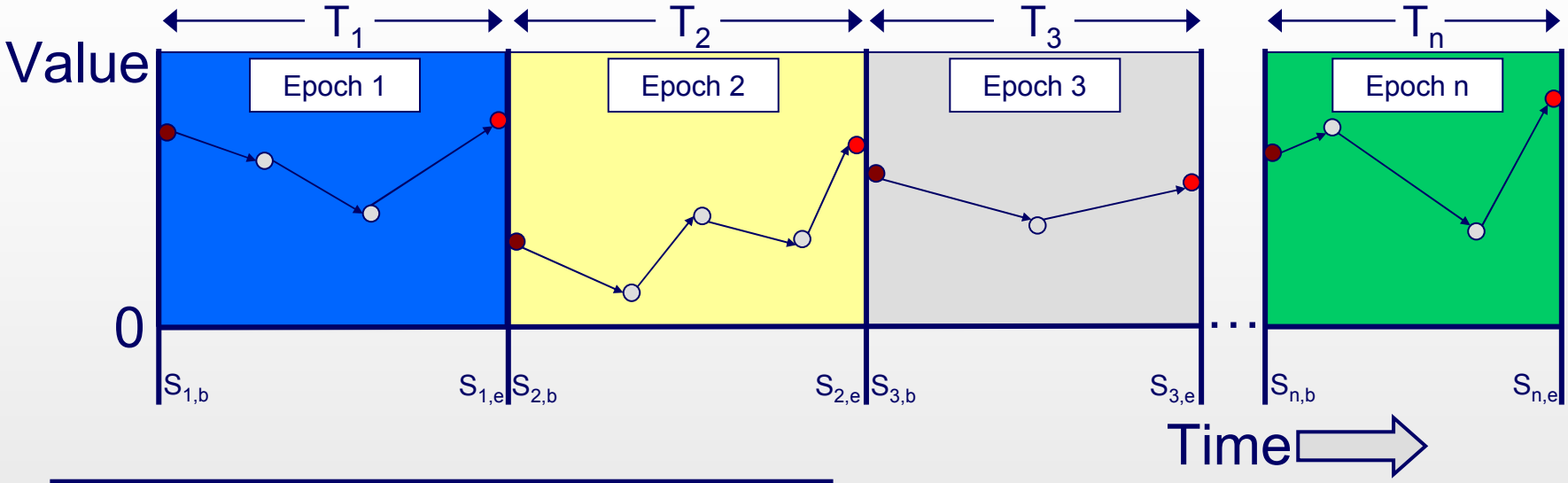
The System Change Timeline



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

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What Can Change: Short Run and Long Run Analysis

In economics, the *short run* is the decision-making period during which at least one input factor is considered fixed

Example: lease on facility (commitment can vary 6 mos to 10 yrs or more)

The *long run* is the decision-making period considered when all inputs are variable

Implication: in short run, optimize subject to fixed constraints; in long run, make strategic decisions to shift possibilities

	Short run		Long run	
	Fixed factors	**Variable factors**	**Fixed factors**	**Variable factors**
Economic Analysis	Input factors such as labor, capital equipment, regulations, knowledge	Quantity demanded, quantity supplied, dollars and time spent	none	all
Engineering Analysis	Objectives, constraints, stakeholder set, technology, concepts	Design chosen, dollars and time spent, perceived value	none	all

Natural analogy from economics to engineering leverages years of methodological validation

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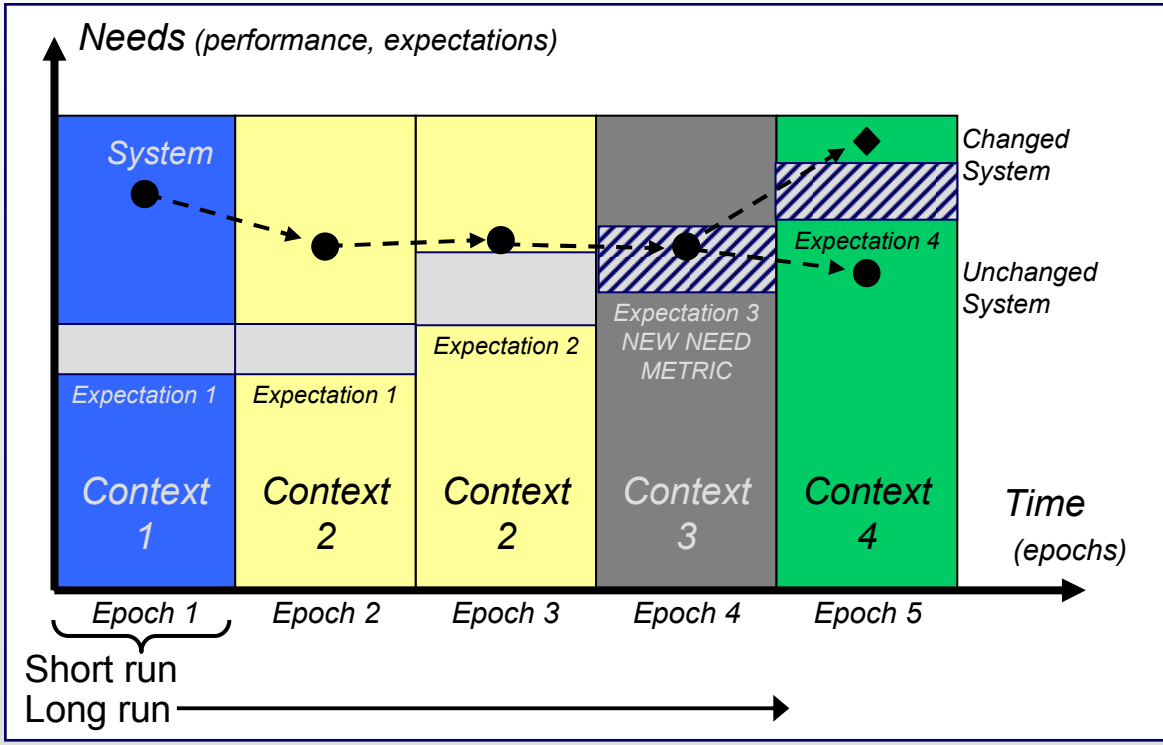
Capturing "Context" Effects on Systems over Time

- Plot performance/expectations vs. time
- Context, system, expectations change in *epochs*



Epoch:

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

Legend

- System
- System Trajectory
- Expectations

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

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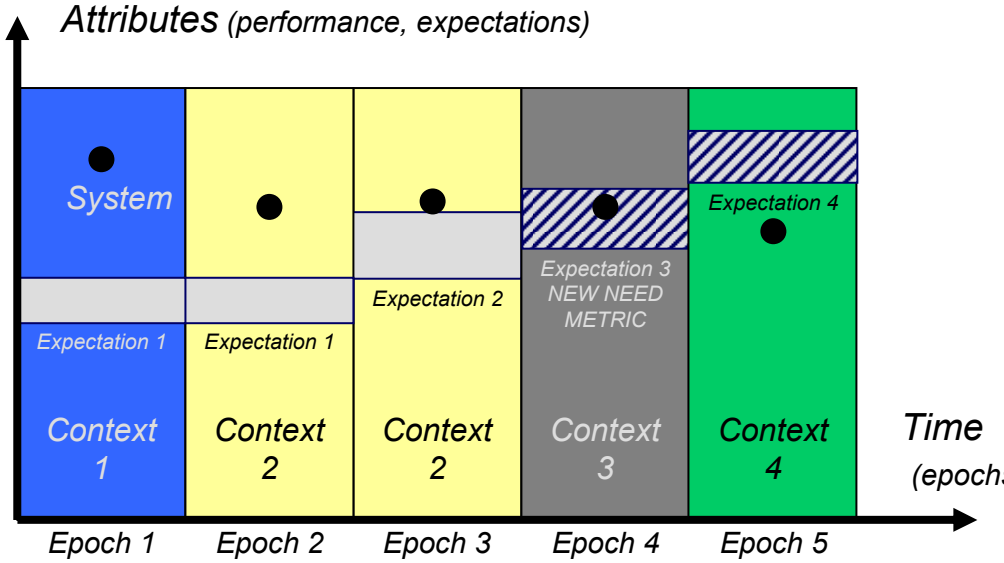
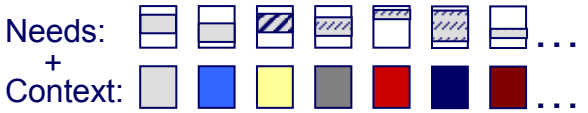
Using Epochs to Represent Context and Expectations

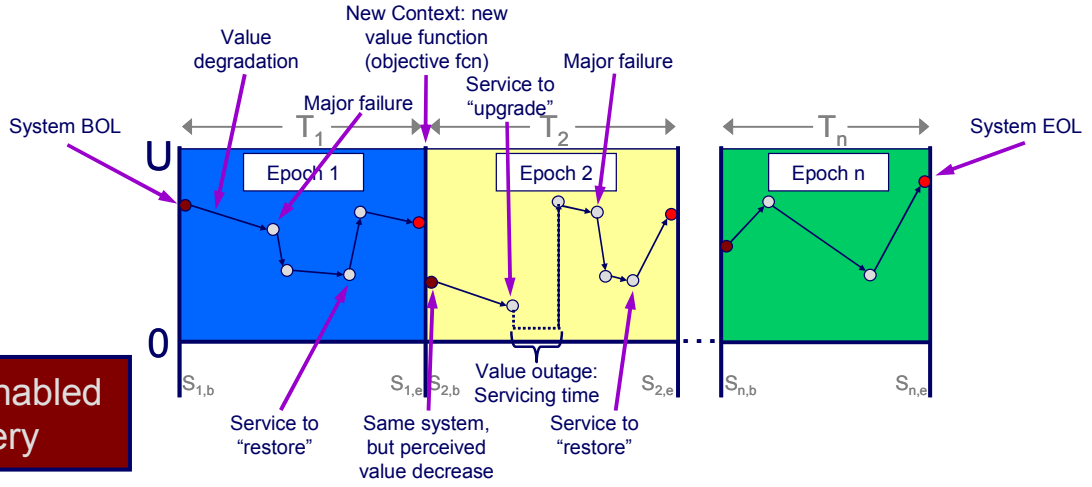


Two aspects to an ***Epoch***:

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



Example system: Serviceable satellite



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

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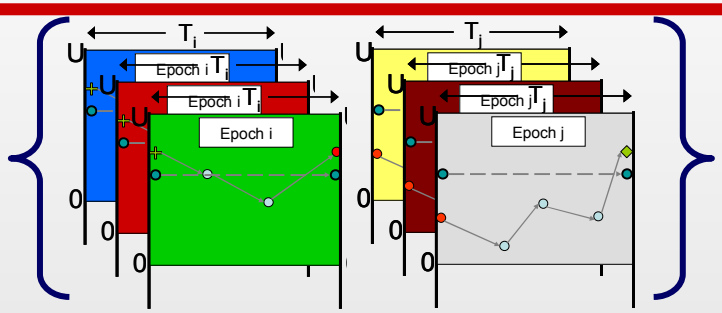
Epoch-Era Analysis: Epochs

Epoch

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

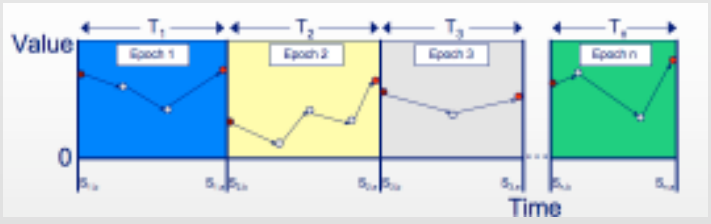
Define Epochs

- 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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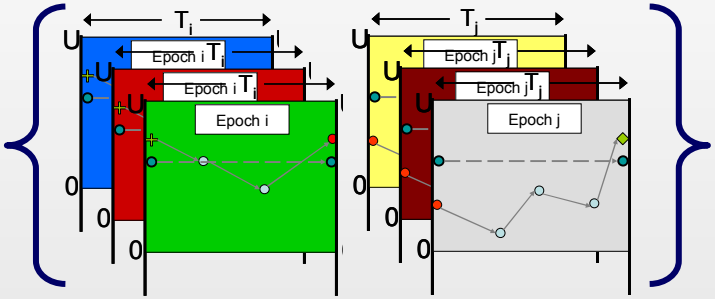
Epoch-Era Analysis: Eras

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

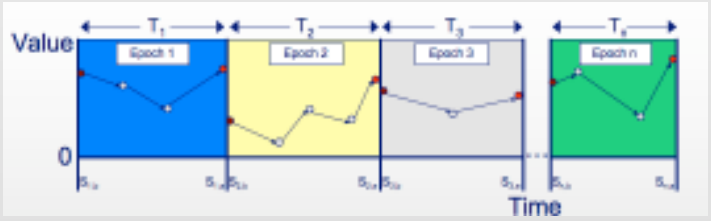
Define Epochs

- 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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Example Scenario: Two Epochs

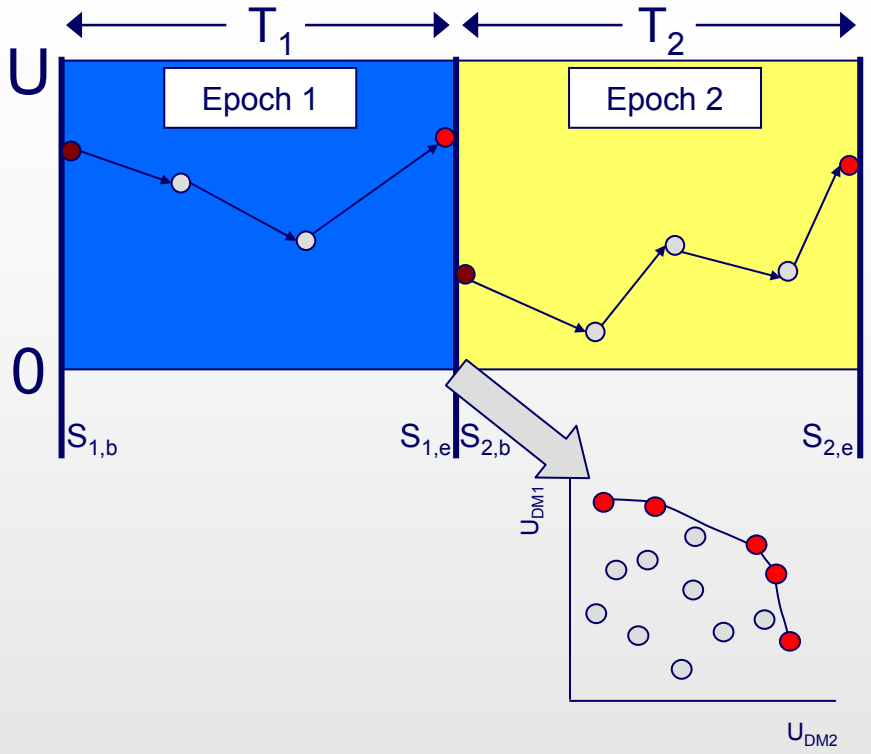
Epoch 1

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)*

Given $S_{1,b}$

Explore $S_{1,e}$

Select $S_{1,e}$

If $S_{2,b}=S_{1,e}$

Explore $S_{2,e}$

Select $S_{2,e}$

New Customers, Changed Constraints, New Concepts

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

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Epoch Usage Considerations

- 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

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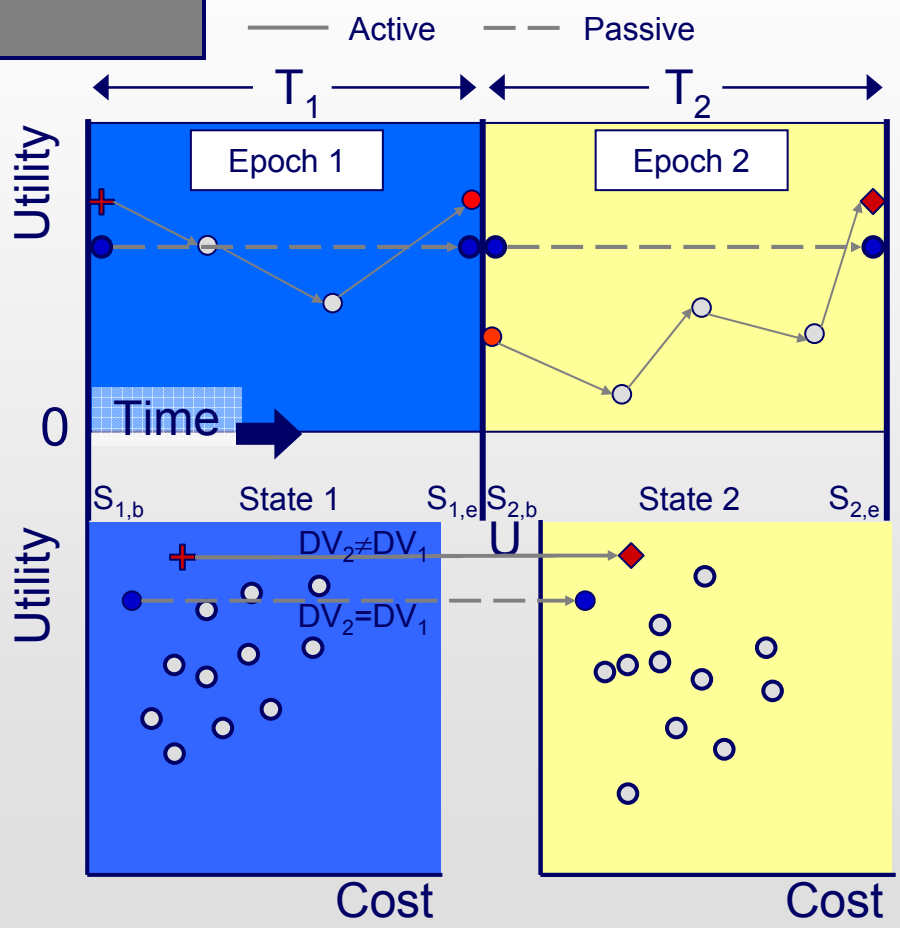
Achieving Value Robustness

Research suggests two strategies for "Value Robustness"

New Context Drivers

- External Constraints
- Design Technologies
- Value Expectations

1. Passive
   - Choose "clever" 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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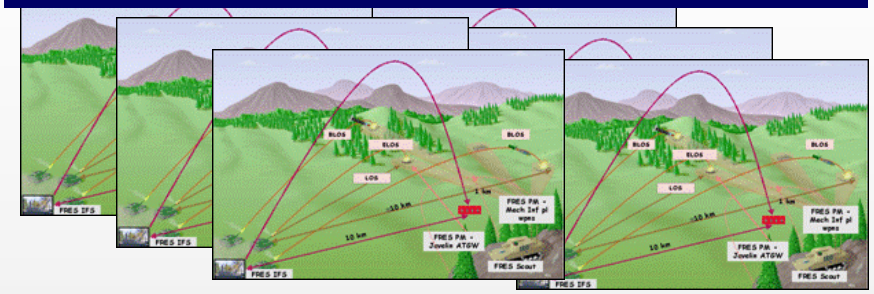
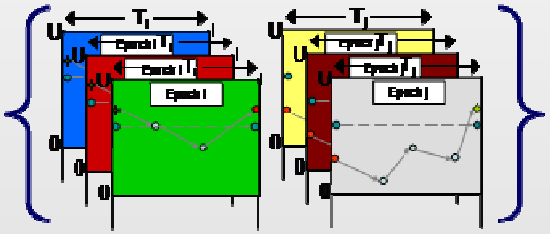
Boundary Spanning Activity

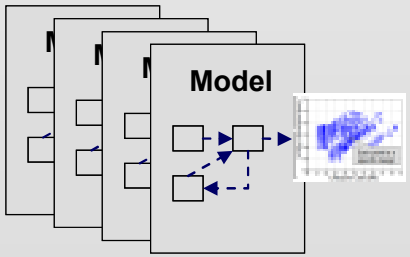
Possible Scenarios and Trajectories



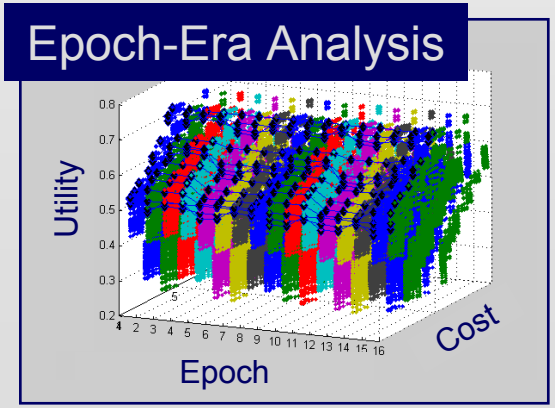
Possible Epochs and Eras



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

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Capturing Information

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

See paper for example

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, $U_i(X_i)$:	Single attribute utility curves for the epoch for each decision maker.
Multi-attribute utility curve, $f(U(k_i,U_i))$: 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, 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.

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Research Directions

Four further research areas

1. Descriptive research on system context and decision analysis processes
2. Synergies with other time-based methods
3. Validation of method on “real” case study
4. Educational constructs for mindset shift

Example open research question: how can this approach be used to represent or quantify system dynamic properties? (i.e. many of the new “ilities”)

Current research project underway for large scale methodological validation through application to a “real” system

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Conclusion

- Epoch-Era Analysis intends to introduce a "natural" value-centric tool for system alternative generation, evaluation, and communication in a dynamic and changing "context"
- Is scalable in application, from qualitative to deeply quantitative
- Useful as boundary object between stakeholders, architects, and analysts
- Force 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

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Thank you!

Any questions?

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

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