Five Aspects of Engineering Complex Systems

Emerging Constructs and Methods

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Topics

- Motivations
- Evolutionary Path of Engineering Practice
- Five Aspects Defined
- Aspect Constructs and Methods
- Combining Aspects
- Multi-Aspect Synthesis
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Motivations

STAKEHOLDER NEEDS CHANGE AS PERCEPTION OF SYSTEM AND VALUE DELIVERED EVOLVES

SYSTEMS EXIST IN DYNAMIC CULTURAL, POLITICAL, FINANCIAL, MARKET ENVIRONMENTS

HIGHLY COMPLEX AND INTERCONNECTED SYSTEMS WITH CHANGING TECHNOLOGY OVER LONG LIFESPANS

Engineering complex systems in a dynamic world requires multi-faceted methods that evolve over time and through synergies of individual research contributions

The engineering of systems has always considered a multitude of dimensions …. and increasingly requires formal methods and enabling technologies to respond to modern challenges

Evolutionary Path

On the development of systems engineering methods…

1. **Initial constructs and conceptual approaches emerge**
2. **Methods improved and enhanced with enabling techniques**
3. **Quantitative approaches formulated and formal methods developed**
4. **Methods made executable via computer-based implementation**

Five Aspects Taxonomy

STRUCTURAL	related to form of system components and their interrelationships
BEHAVIORAL	related to function/performance, operations, and reactions to stimuli
CONTEXTUAL	related to circumstances in which the system or enterprise exists
TEMPORAL	related to the dimensions and properties of systems over time
PERCEPTUAL	related to stakeholder preferences, perceptions and cognitive biases

Example Constructs and Considerations

STRUCTURAL	• heterogeneous components and constituent systems • elaborate networks, loose and tight couplings • layers, vertical/horizontal structures, multiplicity of scales
BEHAVIORAL	• complex variance in response to stimuli • unpredictable behavior of technological connections • emergent social network behavior
CONTEXTUAL	• many complexities and uncertainties in system context • political, economic, environmental, threat, market factors • stakeholder needs profile and overall worldview
TEMPORAL	• decoupled acquisition phases and context shifts • systems with long lifespan and changing characteristics • time-based system properties (flexibility, survivability, etc.)
PERCEPTUAL	• many stakeholder preferences to consider • perception of value shifts changes with context shifts • cognitive constraints and biases

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Contextual Aspect

Contextual Aspect

Requires understanding of complexities/uncertainties stemming from:

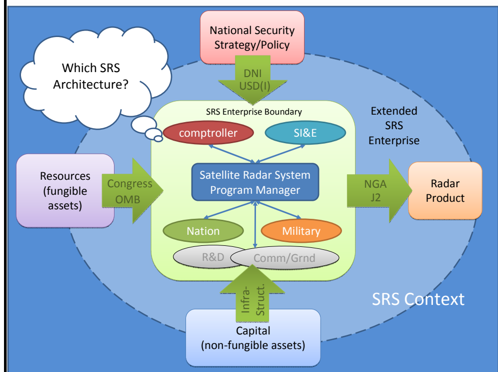
- external environment in which system operates
- relevant stakeholder needs as driven by this environment

Relates to understanding system in a period of fixed context and needs

- context shifts may occur as related to political, economic, threat, cultural, policy, and market factors
- exogenous factors drive design decisions, yet are typically not fully elaborated and considered

Traditional systems engineering includes defining system boundaries, external entities, and external interfaces in system context diagrams. Also described in documents such as operational concept documents or capability description documents. While highly useful, these provide descriptive information rather than an analytic capability.

Contextual Aspect: Model-based Approach



Definition of Epoch

Time period with a fixed context and needs; characterized by static constraints, concepts, available technologies, and articulated expectations

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 (Med),** equiv. TRL = 6 technology **Level 3 (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

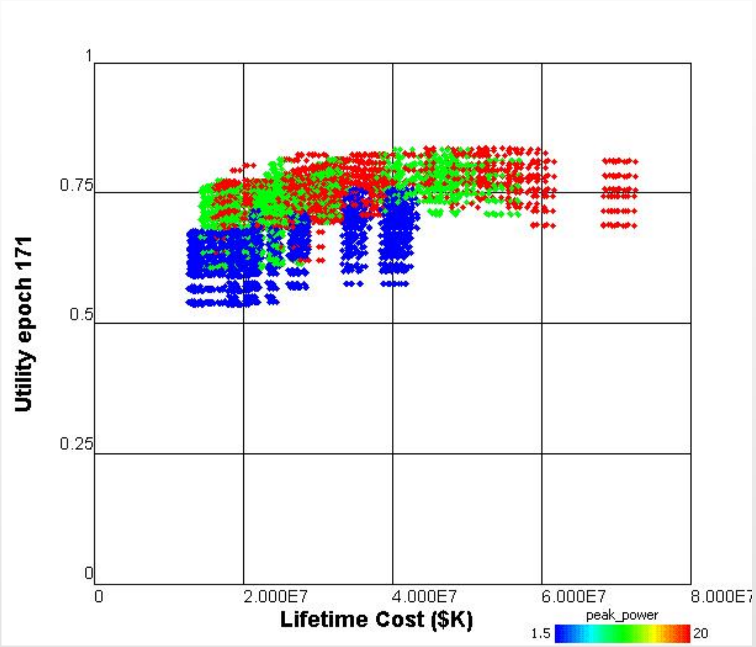
Epoch variables allow for parameterization of some "context" drivers for system value

Contextual Aspect Example: Multi-Epoch Tradespaces

Epoch "171"

Baseline Program Context:

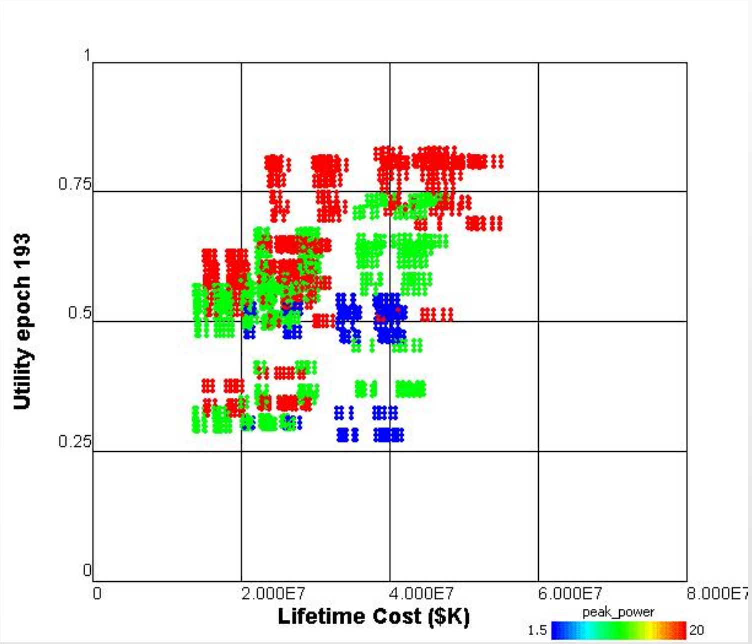
Standalone capability needed, Imaging mission (primary)



Epoch "193"

New Program Context:

Cooperative capability needed, Tracking mission (primary)

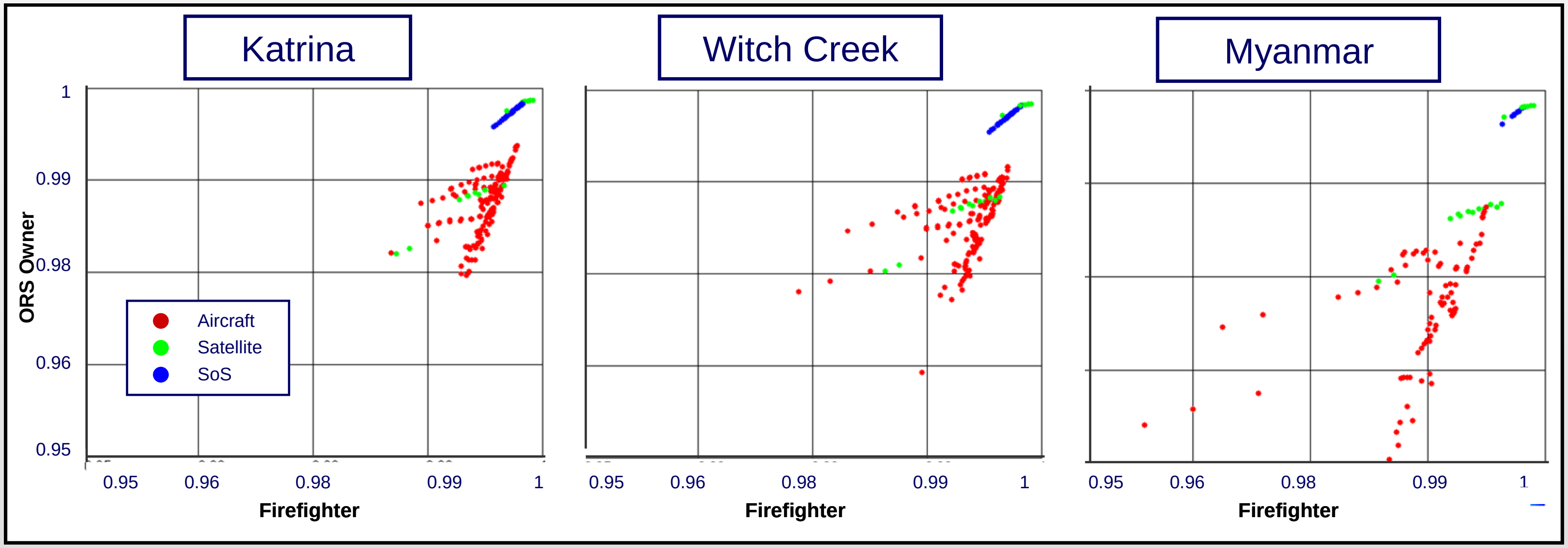


Epoch variables are defined in regard to uncertainties (for example, resources, policy, technology availability, and others). Epochs are computationally generated using the possible permutations of the epoch variable set values. This approach has enabled deeper analysis for assessing performance of concept designs across multiple epochs.

A.M. Ross and D.H. Rhodes, "Using Natural Value-centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis,"18th *INCOSE International Symposium*, Utrecht, the Netherlands, June 2008

Contextual Aspect

Illustrates set of design concepts for an *operationally responsive surveillance system* shown for three epochs (where epoch variables vary based on the characteristics of a context shift (different disaster situation)



D. Chattopadhyay, A.M. Ross and D.H. Rhodes,“ Demonstration of System of Systems Multi-Attribute Tradespace Exploration on a Multi-Concept Surveillance Architecture," *7th Conference on Systems Engineering Research*, Loughborough University, UK, April 2009

Temporal Aspect

Temporal Aspect

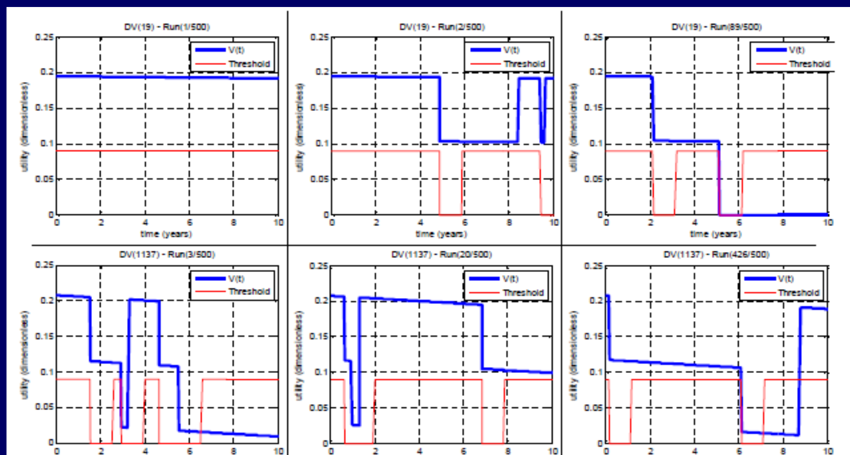
- Temporal aspect of systems is critically important, but remains undertreated in engineering practice
- Use of system scenarios is most typical method used in systems engineering, but largely "illustrative"
- Necessary to characterize changes over time
- Addresses time-based properties such as survivability or adaptability of the system over its lifespan

Over two decades ago, Hall discussed the importance of an environmental forecast ….. "a forecast is daunting because it encompasses a comprehensive description of the environment from before the time of conception of a new system, through every period of its lifecycle, to its ultimate demise".

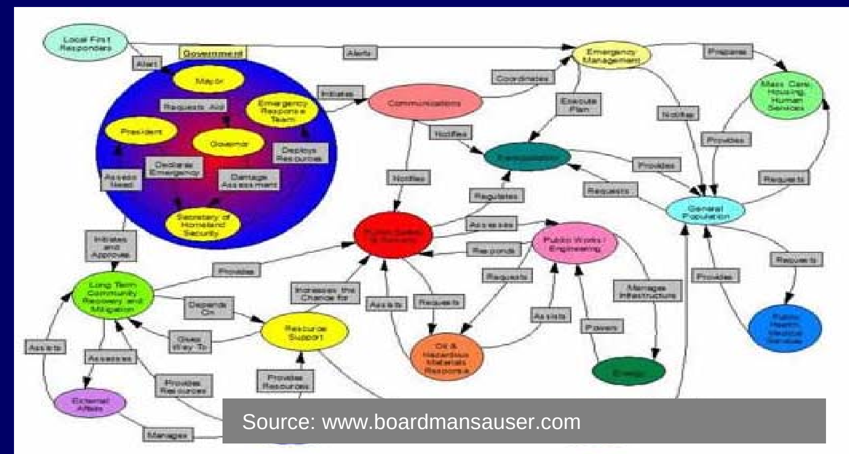
A.D. Hall, *Metasystems Methodology*, Oxford, England, Pergamon Press, 1989

Temporal Aspect

Monte Carlo Simulation



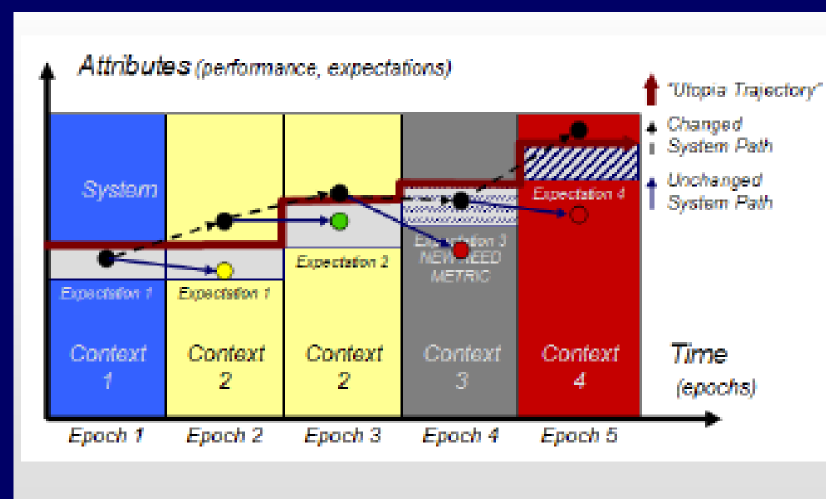
Systemigram (Boardman)



SCENARIO	Buyer behaviour	Consumption patterns Total: Private import:	Consumer sorting behaviour (trends)	National environmental policy	Price of new raw material vs reclaimed material	Production technology: volume of materials	Technology development: reclaiming technology	EU-directives for import and export of waste
Global Crisis (Production gone wild)	Willing to pay more for green products	Total: Up Private import: Up	Voluntary (ideologically driven)	At the forefront; Holistic approach (legal & econ.)	New: High Reclaimed: High	Much less than today	Very rapid increases	Less restricted than today
Raw Material Depletion	Will to buy green, but will not pay more	Total: Status Quo Private import: Up	Will sort for compensation/ reward	At forefront, but no holistic approach (legal only)	New: High Reclaimed: Low	Somewhat less than today	Substantial increases	Same as today
Current policies (Negative trend)	No interest in buying green products	Total: Up Private import: SQ	Will sort if facing sanctions	Ideological, based on voluntary acceptance	New: Low Reclaimed: High	Same as today	Only marginal increases	More restrictive than today
Current policies (Positive trend)		Total: SQ Private import: SQ	Will resist sorting	Least possible adaptation	New: Low Reclaimed: Low			
Green-house effect (Stop emissions)								
Batman: High-tech solutions								
Dematerialised production (New materials)								
Green market (ideological paradise)								

Source: Ritchey, 2009

Morphological Analysis (Ritchey)

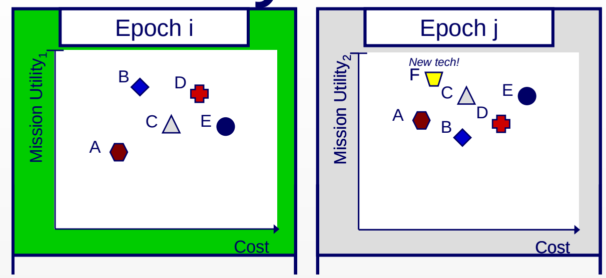


Epoch-Era Analysis (Ross & Rhodes)

Temporal Aspect Example: Epoch-Era Analysis

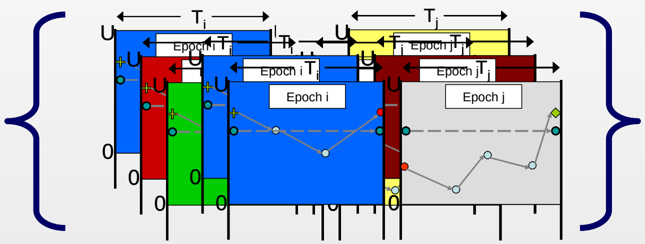
Compare Alternatives

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



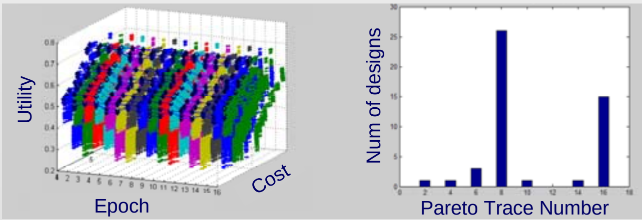
Epoch Characterization

Epoch set represents potential fixed contexts and needs



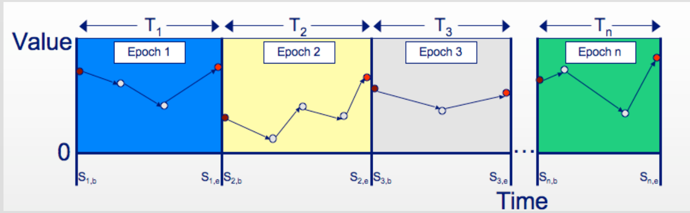
Multi-Epoch Analysis

Analysis across large number of epochs reveals “good” designs



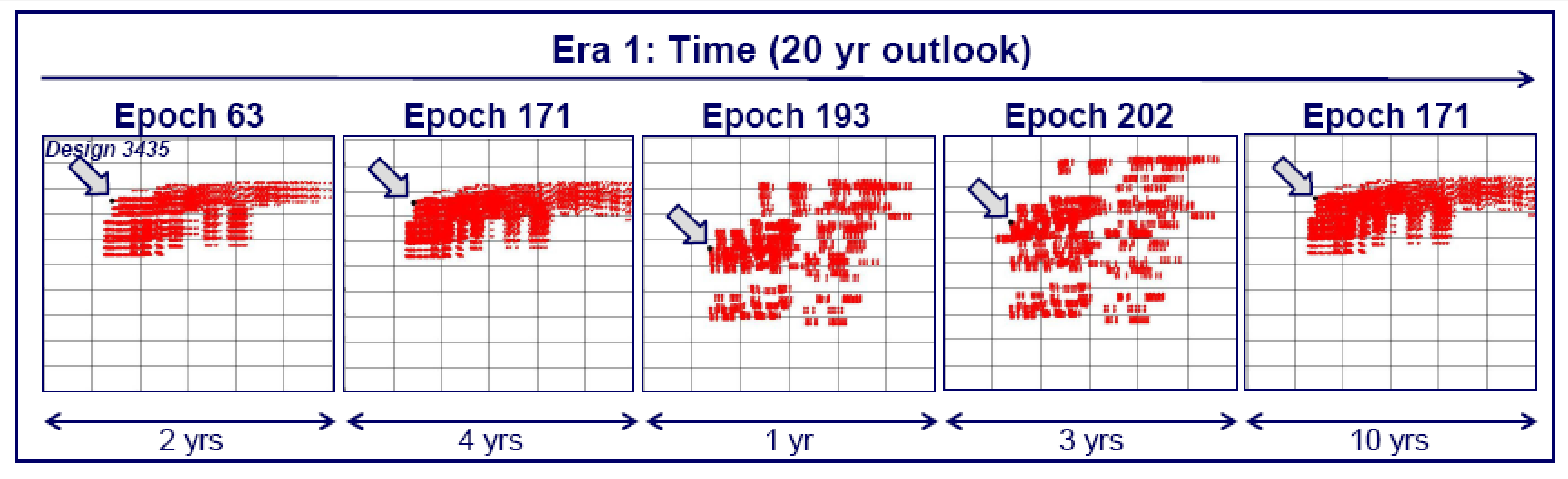
Era Construction

Eras represent ordered epoch series for analyzing system evolution strategies



Temporal Aspect Example: Tradespace Exploration using Epoch-Era Analysis

Value (utility) of designs for cost shown across system era with four epoch shifts (arrow indicates design of interest)



A.M. Ross and D.H. Rhodes, “Using Natural Value-centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis,”18th *INCOSE International Symposium*, Utrecht, the Netherlands, June 2008.

C..J. Roberts, M.G. Richards, A.M. Ross, D.H. Rhodes, and D.E. Hastings, "Scenario Planning in Dynamic Multi-Attribute Tradespace Exploration," *3rd Annual IEEE Systems Conference*, Vancouver, Canada, March 2009

Perceptual Aspect

Perceptual Aspect

- Relates to how system is interpreted through perspective of stakeholders
- Considers individual stakeholder preferences, and how preferences vary across stakeholders
- Considers changes in preferences as response to context shifts over time as stakeholders interact with system in its environment.
- Includes cognitive limitations, biases, and preferences of stakeholders

Systems are valuable only when perceived as such by stakeholders

Accordingly methods need to address perceptual aspects of engineering systems

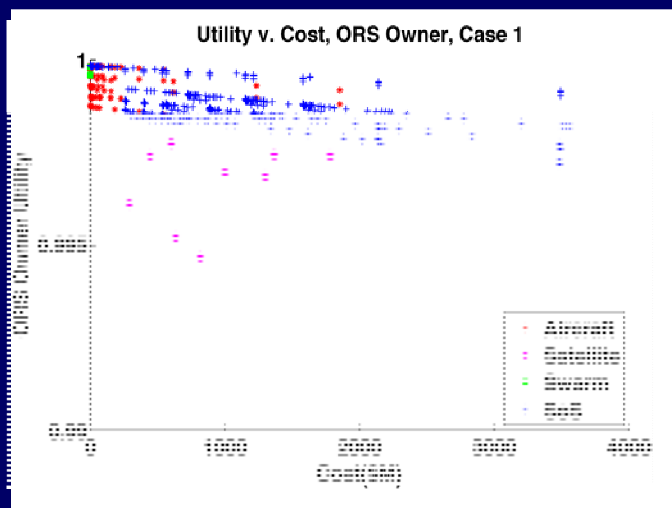
As systems grow increasing complex, the human-system dimensions present greater challenges.

Systems Engineering Advancement Research Initiative

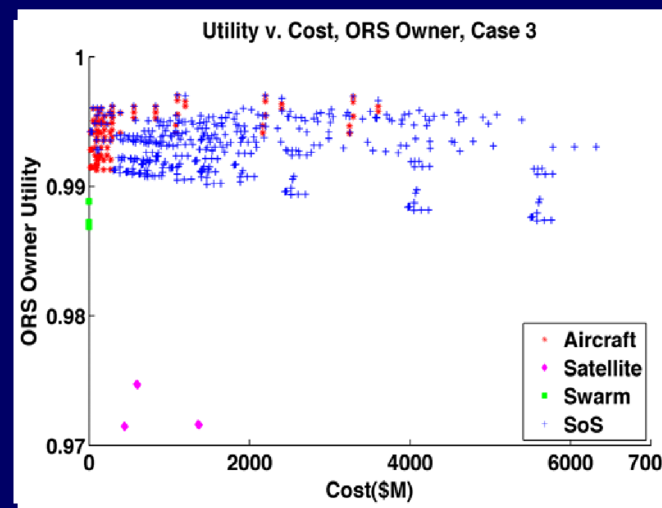
Perceptual Aspect Example: Shift in What Stakeholder Values

Perceptual aspect can relate to need to understand 'goodness' of design concepts as a stakeholder's preferences shift over time. Exogenous factors such as economic changes, available technology, threats and other factors may influence relative importance of what a stakeholder values.

Original Attribute Relative Weights



Changed Attribute Relative Weights



Impact of Change in Stakeholder Weighting of Desired System Attributes in Tradespace showing Utility vs Cost for a Multi-Concept System

D. Chattopadhyay, A.M. Ross and D.H. Rhodes," Demonstration of System of Systems Multi-Attribute Tradespace Exploration on a Multi-Concept Surveillance Architecture," *7th Conference on Systems Engineering Research*, Loughborough University, UK, April 2009

Combining Aspects

Combining Aspects

- Framework offers means to consider useful constructs and methods relevant to the individual aspect under consideration
- More powerful use of framework is potential for methodological innovations through combining aspects

Combinatorial approaches have been shown as sources for innovation

- *Example: research on a value-based design attribute classification framework demonstrated how new sources of value can be uncovered through intentional combinations of system attributes*

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

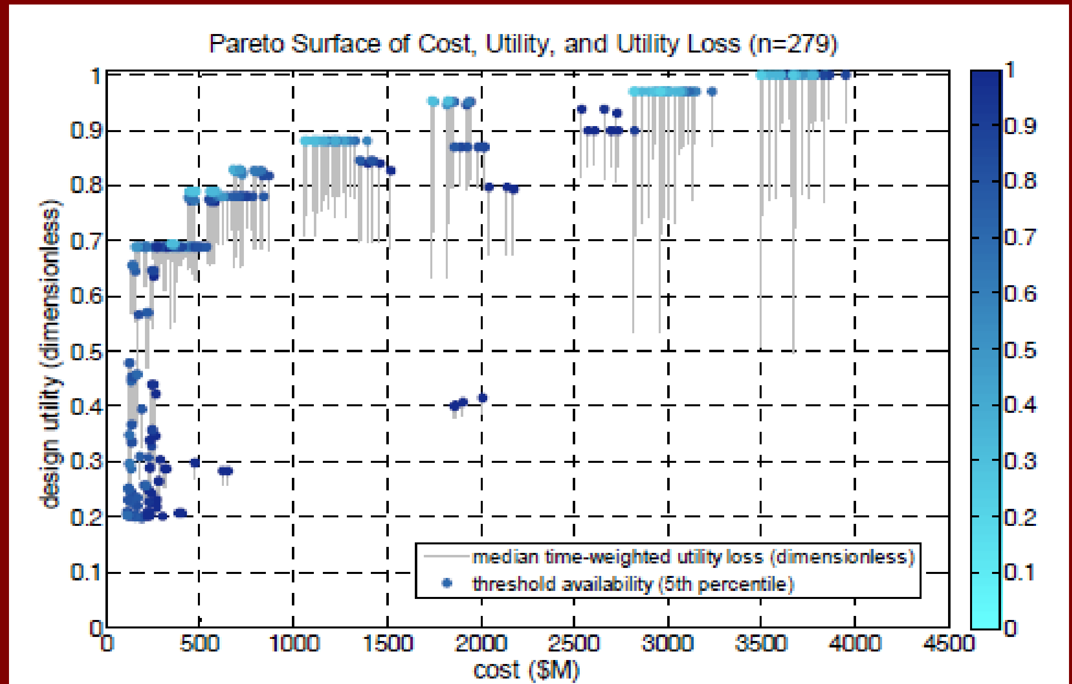
Example: History of Combining Structural and Behavioral Aspects

Emergence of Model-Based Systems Engineering (examples initiatives)	
1987	Descriptive method with function and physical (structural) and operational (behavioral) views, implemented in early computer based environment L. Karas, and D.H. Rhodes, Systems Engineering Technique, *Design, Development and Testing of Complex Avionics Systems: Conference Proceedings*, 1987
1997	Prescriptive approach for engineering complex systems using structural and behavioral system models D. Oliver, T. Kelliher, and J. Keegan,, *Engineering Complex Systems with Objects and Models*, NY: McGraw Hill, 1997
2007	Initial publication of INCOSE Survey of six leading MBSE methodologies with enabling toolset environment INCOSE TD-2007-003-01, Survey of Model-Based Systems Engineering Methodologies, 10 June 2008

Combining Aspects Example: Temporal and Perceptual

What visual construct can combine:

- ***temporal aspect*** (effective display of time-based impacts) *and*
- ***perceptual aspect*** (ability of decision maker to cognitively process complex tradespace information)?



Richards (2009): Perceptually understandable display of value for cost of satellite radar designs with time-based information on survivability of system as it experiences possible finite disturbances over its lifespan

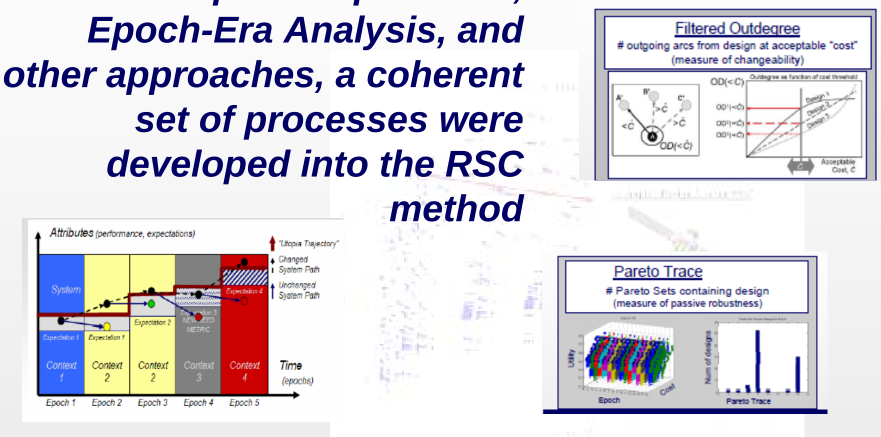
Amount of information and complexities within a set of information are challenges, in that human cognitive limits for processing the visual display must be considered, as well as mechanism to compute and display synthesis of temporal analysis (survivability over system life)

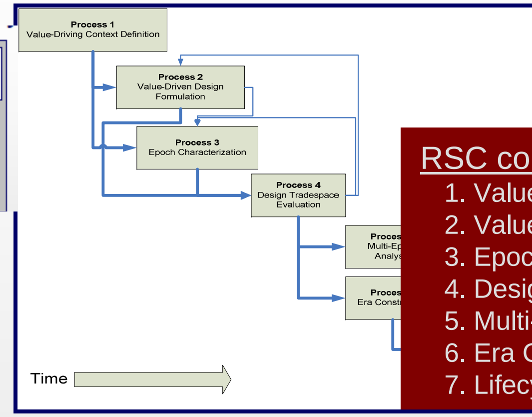
Multi-Aspect Synthesis

Multi-Aspect Synthesis Example:

Responsive Systems Comparison (RSC)

Using Multi-Attribute Tradespace Exploration, Epoch-Era Analysis, and other approaches, a coherent set of processes were developed into the RSC method





RSC consists of seven processes:

1. Value-Driving Context Definition
2. Value-Driven Design Formulation
3. Epoch Characterization
4. Design Tradespace Evaluation
5. Multi-Epoch Analysis
6. Era Construction
7. Lifecycle Path Analysis

Seeking ways to combine multiple aspects is a source for further methodological innovation

Synthesis of multi-aspect methods can be used to develop robust methods for engineering complex systems

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

Multi-Aspect Synthesis: Ongoing RSC Method Development

aspect	Research outcome example	Ongoing research example
Contextual	Epoch Characterization: in the method each fixed period of context and needs (an epoch) is modeled by characterization and parameterization of exogenous uncertainties	Continuing research includes empirical studies to **understand the driving epoch uncertainties across different domains** including space, aerospace, transportation, and energy
Temporal	Multi-Epoch Analysis: once epochs are modeled, analysis is performed to assess how designs perform across multiple epochs	Continuing research includes investigating **how viable ordered sequences of epochs can be generated/used** in temporal-based analysis
Perceptual	Visualizing Complex Tradespaces: complex data sets are generated using RSC, researchers have developed several effective constructs given human cognitive limitations/preferences	Continuing research includes investigation of how to present analysis results to **accommodate cognitive preferences and biases of different stakeholders** such as senior decision makers and legislative aides

Five Aspects Framework: Future Directions

1. Further testing and validation of aspects
2. Frame for exploring related research
3. Use as taxonomy for classifying research

Through classifying research using the framework, there is opportunity to seek similar research within and across domains, and to combine research outcomes within aspects, across aspects and through broad synthesis.

Studies from the other domains can uncover context factors not previously considered, and validate the importance of thinking about context in system design

Example: investigation of context aspect has uncovered similar inquiry in other domains:

- field of organizational behavior: importance of understanding influences of external environment on individuals to understand organizational behavior
- field of computer science: empirical study of 150 participants identified external contextual factors of importance that induce change in information systems

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Summary

Taxonomy provides…

- Distinct viewpoints for defining constructs and methods
- Encourages innovation via combination and synthesis
- Focusing mechanism for finding related research
- Organizing framework for research portfolio

STRUCTURAL *related to the form of system components and their interrelationships* **BEHAVIORAL** *related to performance, operations, and reactions to stimuli*	"State of the Practice" systems architecting and design, and emerging model-based systems engineering approaches
CONTEXTUAL *related to circumstances in which the system exists* **TEMPORAL** *related to dimensions and properties of systems over time* **PERCEPTUAL** *related to stakeholder preferences, perceptions and cognitive biases*	New constructs and methods seek to advance "state of art", for example: *Epoch Modeling* *Multi-Epoch Analysis* *Epoch-Era Analysis* *Multi-Stakeholder Negotiations* *Visualization of Complex Data Sets*

Rhodes, D. and Ross, A., *Five Aspects of Engineering Complex Systems: Emerging Constructs and Methods*, IEEE Systems Conference, April 2010

Rhodes, D. and Ross, A., *Shaping Socio-technical System Innovation Strategies using the Five Aspects Taxonomy, 7th European Systems Engineering Conference, May 2010*