Systems Engineering Advancement Research Initiative

A Methodological Comparison of Monte Carlo Simulation and Epoch-Era Analysis for Tradespace Exploration in an Uncertain Environment

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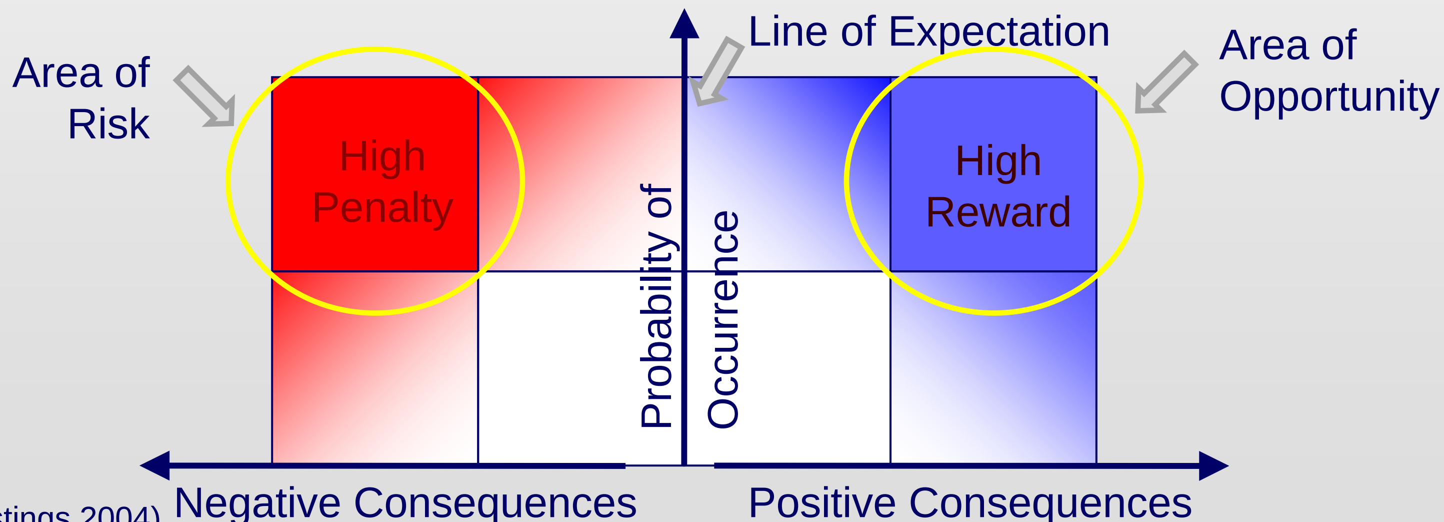
4th Annual IEEE Systems Conference
April 5-8, 2010

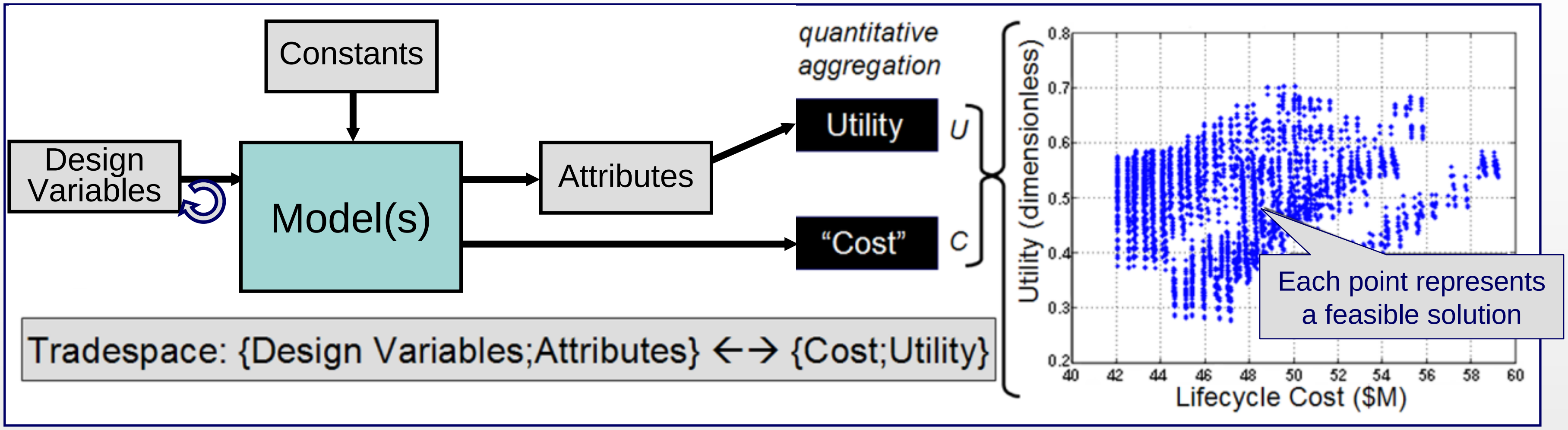
Uncertainty in Design

- Designers face exogenous & endogenous uncertainties
  - User requirements & constraints (exogenous)
  - Economic & political environment (exogenous)
  - Operational environment (exogenous)
  - Actual vs. expected/simulated performance; “model uncertainties” (endogenous)
- Uncertainty leads to both ***risks*** & ***opportunities***



(Walton and Hastings 2004)

Value-Driven Tradespace Exploration

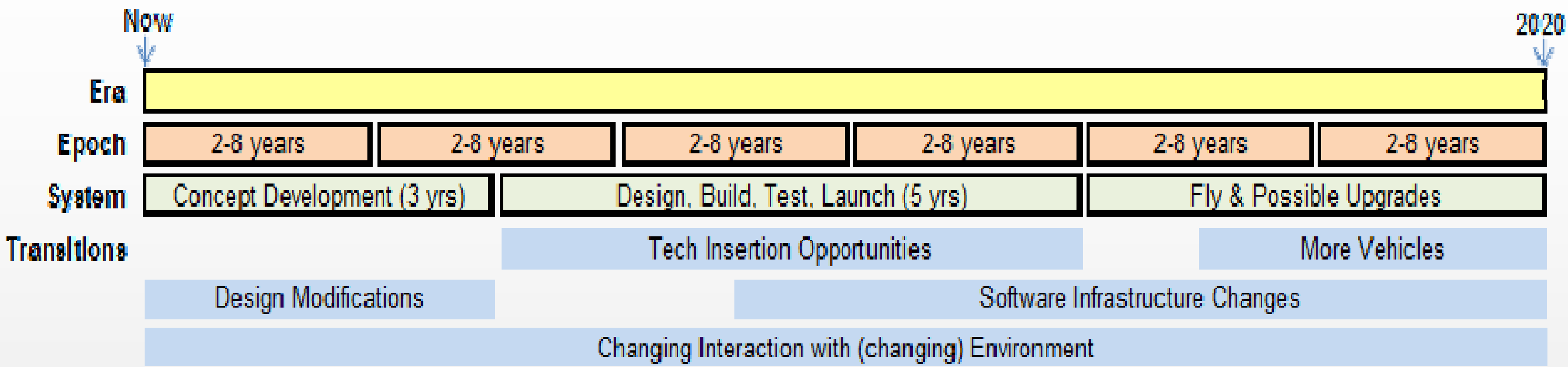


- Model-based, high-level assessment of system capabilities
- Ideally, *many* designs assessed
- Avoids optimized *point solutions* that will not support evolution in environment or user needs
- Provides a way to assess the value of *potential* capabilities
- Provides a basis to explore technical and policy *uncertainties*

(Ross and Hastings 2005)

Enhances informed "upfront" decisions and planning

Challenge: Managing System Uncertainty across the Lifecycle

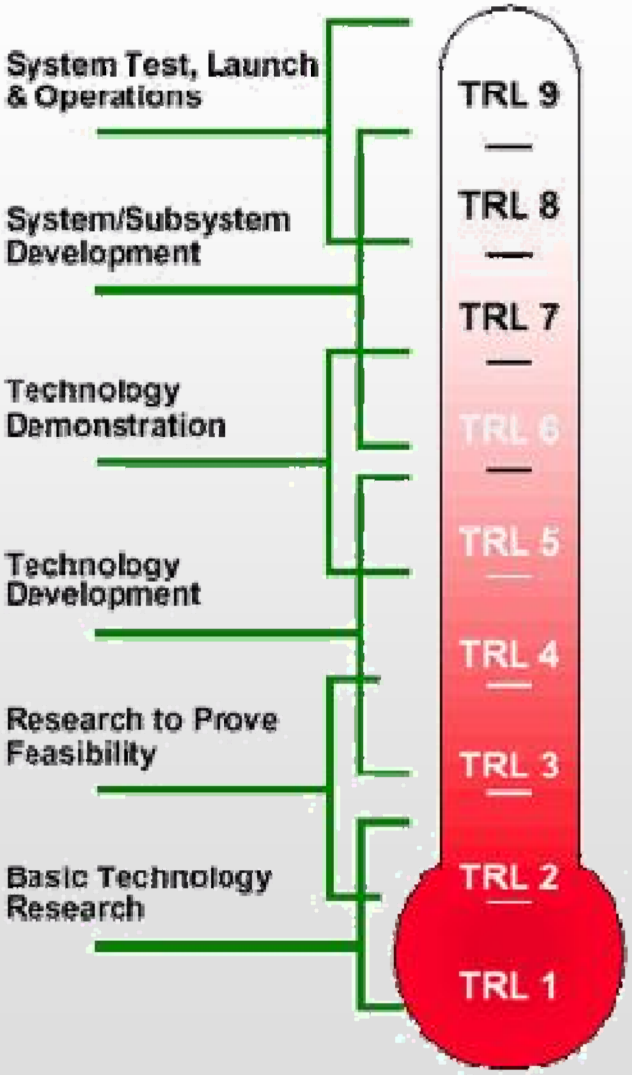


- Shift in contexts occur more frequently than typical high-cost system development timelines (e.g., budgets, leadership, warfighter needs)
- These uncertain fluctuations feed back on programs, creating cost, schedule, and performance risks
- Maximizing lifecycle ***value*** (a contextual, multi-dimensional, and dynamic multi-stakeholder concept) requires quantification of uncertainty at an early stage

How can we account for these uncertainties in order to maximize expected system lifecycle value during "up-front" SE?

Methods of Accounting for Uncertainty

- Qualitative methods
  - Ranking/sorting/categorizing: “low-risk”, “medium risk”, “high-risk”
  - Futures techniques, morphological analysis, scenario planning
- Semi-quantitative methods (can be used to initialize quantitative methods)
  - Technology readiness levels (TRLs)
  - Margins (estimates based on historical performance)



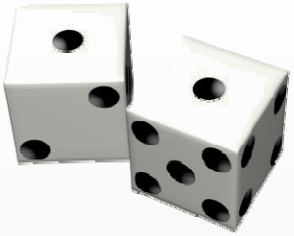
(Thornton 2004, NASA 2007)

Quantitative Methods

- Originally from economics research (maximize return on investment) (Knight 1965; von Neumann and Morgenstern 1944)
- Quantitative methods usually generate probability density functions (PDFs) of expected outcomes
- Designer can isolate designs corresponding to confidence intervals (e.g., 90%, 95%, 99%)
  - Probabilistic risk assessment (PRA), Fault Tree Analysis (FTA), Hazards Analysis (HA), Failure modes and effects analysis (FMEA), Monte Carlo Simulation (MCS), Epoch Era Analysis (EEA)

Most useful for tradespace exploration, which allows us to examine value tradeoffs of many designs on a common basis

Monte Carlo Simulation



Q: What is the expected outcome distribution given quantifiable systematic uncertainties?

- Developed in 1940s
  (Metropolis and Ulam 1949)
- Relies on repeated random/pseudo-random sampling
- Can be applied to problems that are not deterministically solvable

"Top-down" or "bottom-up" probabilistic view of uncertainty

Define N uncertain input variables

↓

Randomly sample M values from each input variable distributions

↓

Calculate M values of ***each*** output variable using simulation model and each random sample

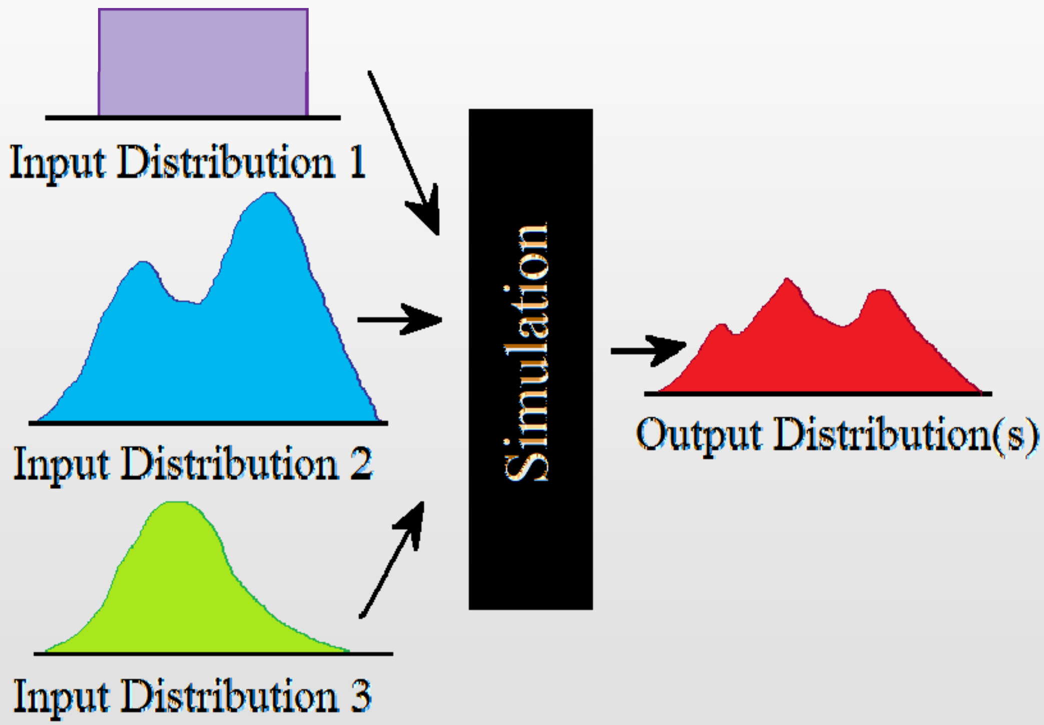
↓

Plot resulting probability distribution(s) of output variables

Iterate as necessary to examine new input variables or distributions

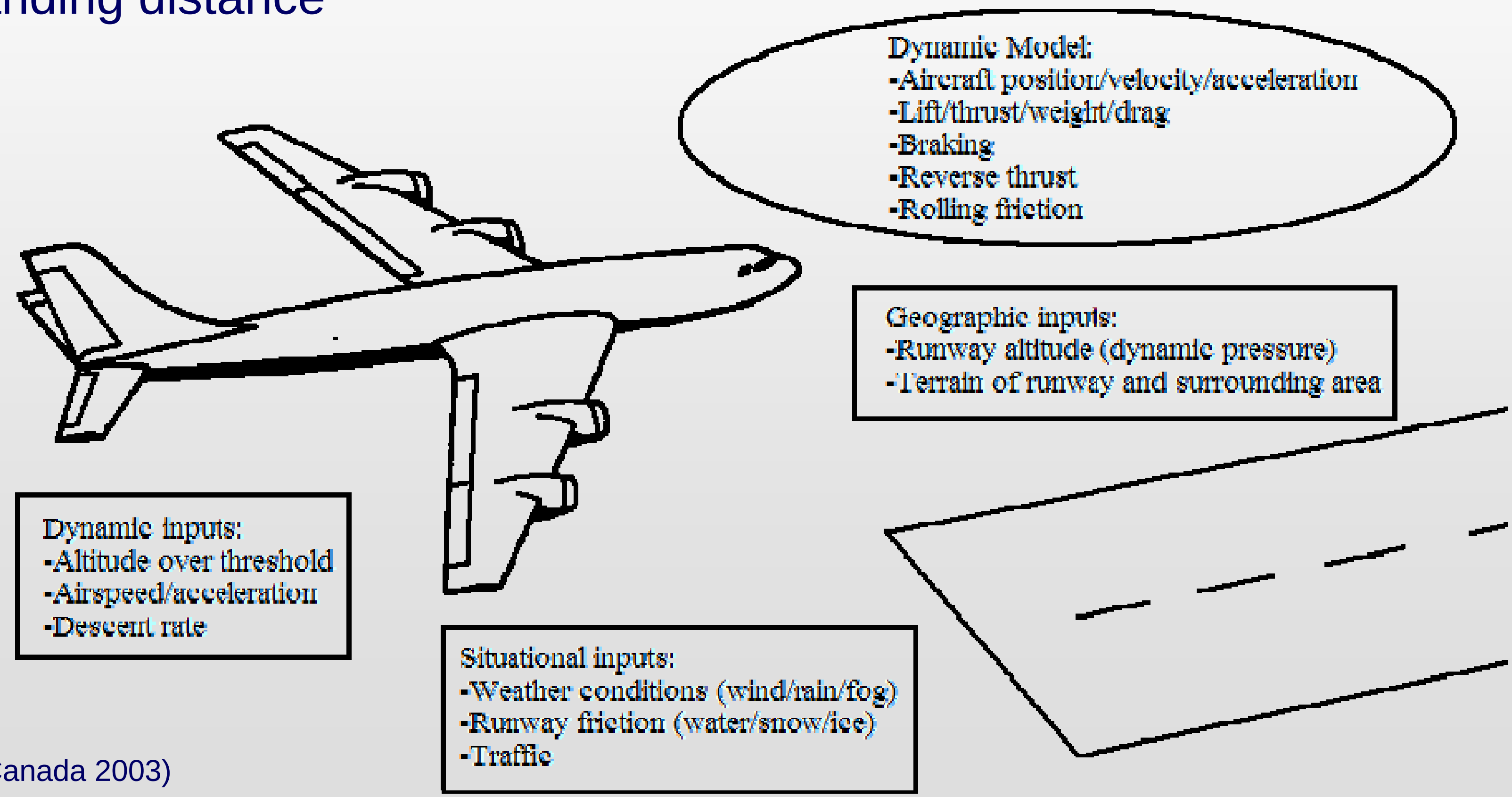
Characteristics of Monte Carlo Simulation

- Numerically formulated
- Wide range of types and applications
- Ideal for problems with a large number of uncertainties for which probability distributions can be estimated
- Results dependent on probability distributions and sampling



Example MCS Application: Aircraft Landing Distance

- Pilots add 15% for rain, 30% for snow ice (based on expert opinion and historical performance)
- Instead, we can use a dynamic model to estimate the expected landing distance



(Transport Canada 2003)

Epoch-Era Analysis

Q: What is the expected value distribution given an uncertain future environment?

- Scenario planning method that provides a structured way to analyze temporal system value
- System lifecycle (comprising an era) is divided into epochs
- Each epoch is described by an epoch vector that defines its key exogenous factors describing the system context

"Top-down" or "bottom-up" "possibilistic" and temporal-based view of uncertainty

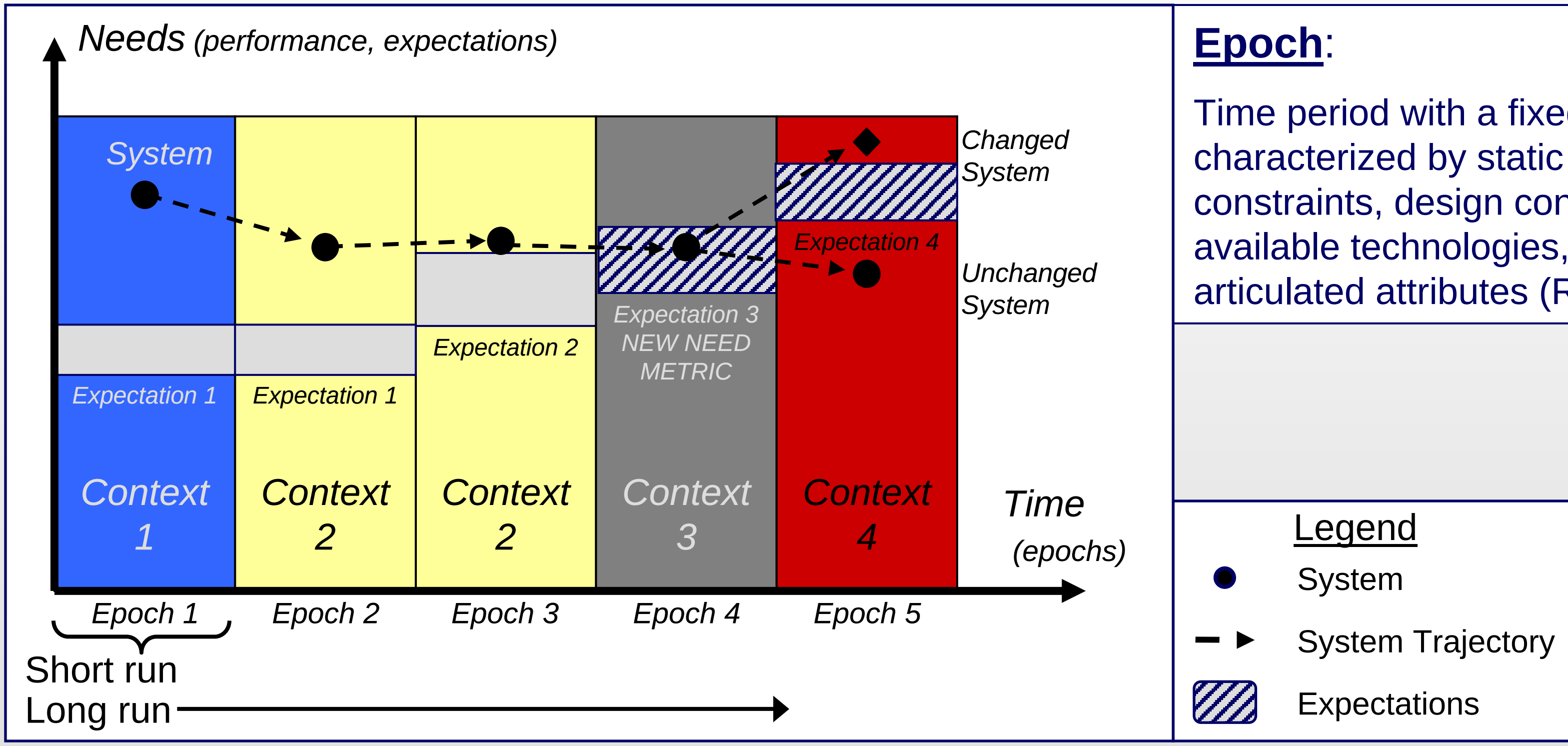
How does one account for exogenous uncertainties?

Identify possible, likely, or consequential uncertain exogenous factors from categories below

Epoch variable categories

- Policy
- Funding
- Infrastructure
- Technology
- Environment

Capturing "Context" Effects on Systems over Time



Epoch:

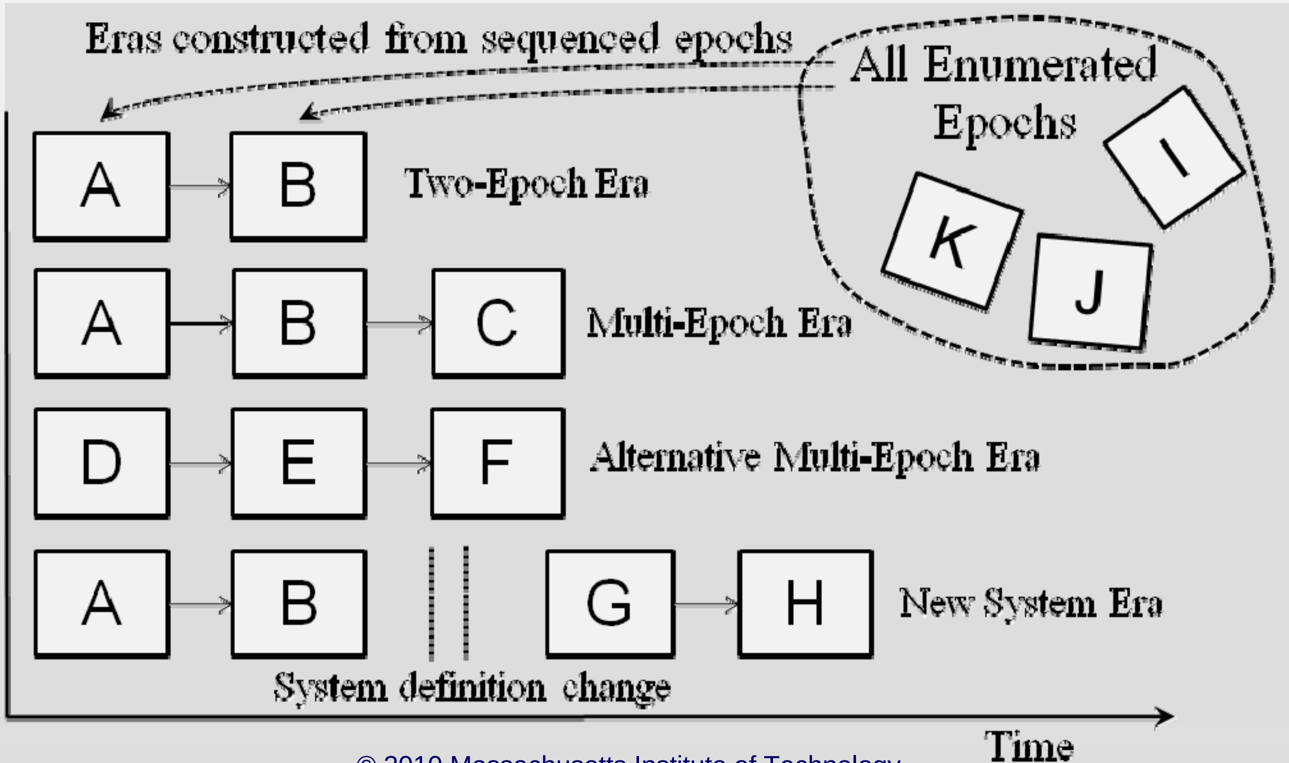
Time period with a fixed context; characterized by static constraints, design concepts, available technologies, and articulated attributes (Ross 2006)

(Ross and Rhodes 2008)

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

Epoch-Era Analysis Steps

1. Multi-stakeholder value definitions
2. Epoch enumeration (define possible futures)
3. Era construction (generate, sample, and assemble futures)
4. Value-based comparison of competing designs



Characteristics of Epoch-Era Analysis

- Eras can be numerically or narratively formulated
- Particularly well suited to mental-model building, even when knowledge of probabilities is unknown
- Epochs can be “hand-picked” to fit imagined scenarios, or automatically selected
- Structured framework guides utility vs. cost tradeoff throughout alternative possible futures
- Sequential ordering of epochs produces an ***emergent path dependence*** of value over time (i.e., the optimal design may depend on *order* of future events)
- Results dependent on epoch enumeration, epoch sampling, and era construction

(Roberts et al. 2009)

Example EEA Application: Satellite Radar System

- Space systems are especially vulnerable to economic, political, and operational uncertainties
- SRS value proposition: “24-hour, all weather imaging and tracking of targets anywhere on the globe”
  - Two primary missions: tracking and imaging
- Endogenous variables (expected system performance) considered deterministic
- Exogenous uncertainties (user requirements, national priorities, available technology, communications infrastructure, and collaborative assets) varied across epochs
- Enumeration ranges and sampling suggestions were established using interviews of domain experts

From: (Roberts et al. 2009)

Epoch Enumeration

Epoch variables (# of levels)	Enumeration levels
Imaging vs. tracking utility priorities (3)	1. Imaging > Tracking 2. Imaging = Tracking 3. Imaging < Tracking
Radar technology (3)	1. Basic 2. Medium 3. Advanced
Communications Infrastructure (2)	1. Air Force satellite communications network (AFSCN) 2. Wideband global SATCOM (WGS) + AFSCN
Collaborative Assets (2)	Airborne intelligence, surveillance, and reconnaissance (AISR) available? (1. yes or 2. no)
Operational plans (9)	1 of 9 possible mission profiles
Threat environment (2)	1. Jamming present 2. No jamming

Enumeration	Sampling
Total 3×3×2×2×9×2 = 648 potential epochs (224 randomly selected, 21 hand-picked)	

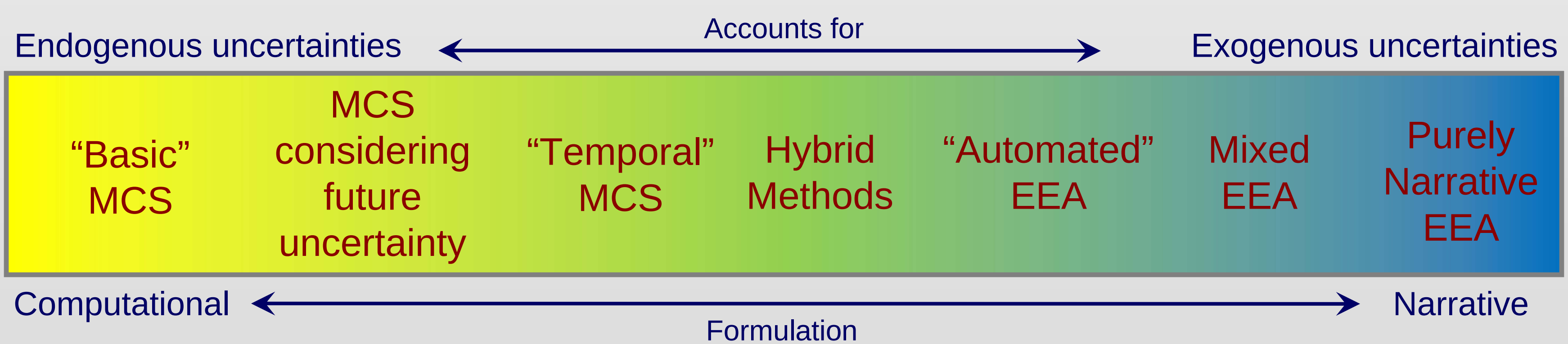
Era Construction

- Era length defined as 20 years
- Epoch length dependent on factors causing epoch shift (time scale of change for that variable, e.g. tech)
- Epoch transition logic not constrained, except no technology regression
- Eras constructed using computer-augmented morphological approach to form 7 eras
- Tradespace exploration (TSE) used to compare many system alternatives' values
- EEA combined with TSE allowed a visual comparison of utility-cost tradeoffs to identify value-robust designs

Structured process for constructing long-run scenarios and mental models

Overlap of MCS and EEA

- MCS and EEA each take many forms, and can overlap in their formulation
- For example, a MCS that uses stochastic dynamic programming can account for temporal uncertainties by breaking the problem down into recursive sub-problems and using decision rules at each stage
- MCS can also incorporate inputs that vary based on scenario or current state
  – i.e., in some cases MCS and EEA address the same problem type



Combining MCS and EEA

- MCS and EEA seek to answer different questions:

MCS: What is the expected outcome distribution given quantifiable systematic uncertainties?

EEA: What is the expected value distribution given an uncertain future environment?

- As such, MCS and EEA are not mutually exclusive, and they can be combined:
  - MCS can be used to quantify a range of system performance (endogenous uncertainty), while EEA can be used to examine the additional effects of exogenous uncertainties such as changing user requirements
  - EEA can enumerate epochs, while MCS can be used for epoch sampling and era construction as part of EEA (preventing biases that could result from hand-picking)

Example Hybrid MCS – EEA Application: Space Tug

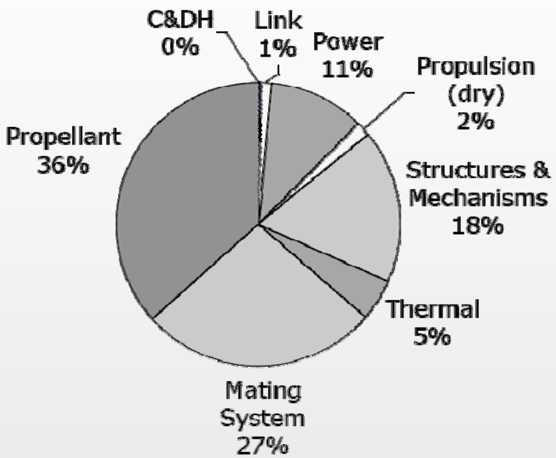
http://www.spaceref.com/news/viewsr.html?pid=10083

- Orbital transfer vehicle ("space tug") concepts face significant endogenous uncertainties (performance) and exogenous uncertainties (mission requirements)
- Some missions require manipulation of heavy payloads (high thrust), some require flexibility to make orbital maneuvers, and efficiency (high delta-V) reduces lifecycle cost
- This tradeoff favors designs that are versatile enough to maintain value in the face of dynamic and uncertain future contexts

From (McManus et al. 2007)

Space Tug Classes

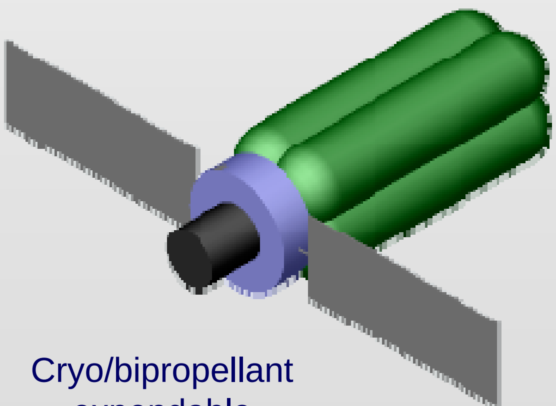
- Four classes of space tug were considered:
  - Bipropellant fuel, cryogenic fuel, electric engine, and nuclear propulsion
- Within each class, 32 designs of each propulsion type (128 total) were initially considered (4 payload capabilities x 8 propellant tank volumes)
- The expected cost and performance (thrust, delta-V, and flexibility to perform orbital maneuvers) of each design were initially estimated using historical margins



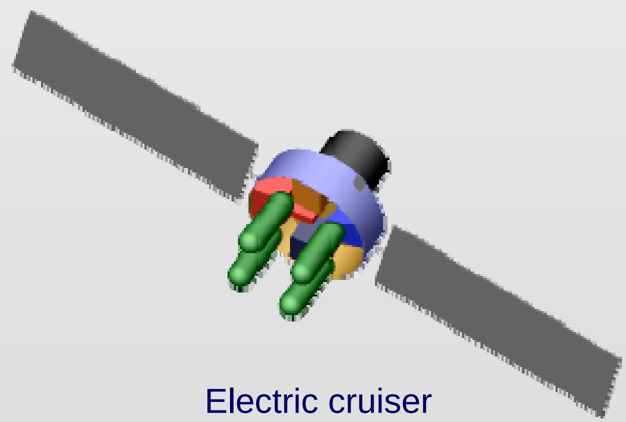
Electric cruiser
Mass breakdown

Epoch-Era Analysis

- Preferences (in terms of utility and cost weighting functions) were varied to form "capability stressed", "efficiency stressed", and "flexibility stressed" epochs (forming single-epoch eras)
- From the initial 128 designs, the most value robust in each class was retained for further analysis using MCS (1 each of bipropellant, cryogenic, electric, and nuclear)



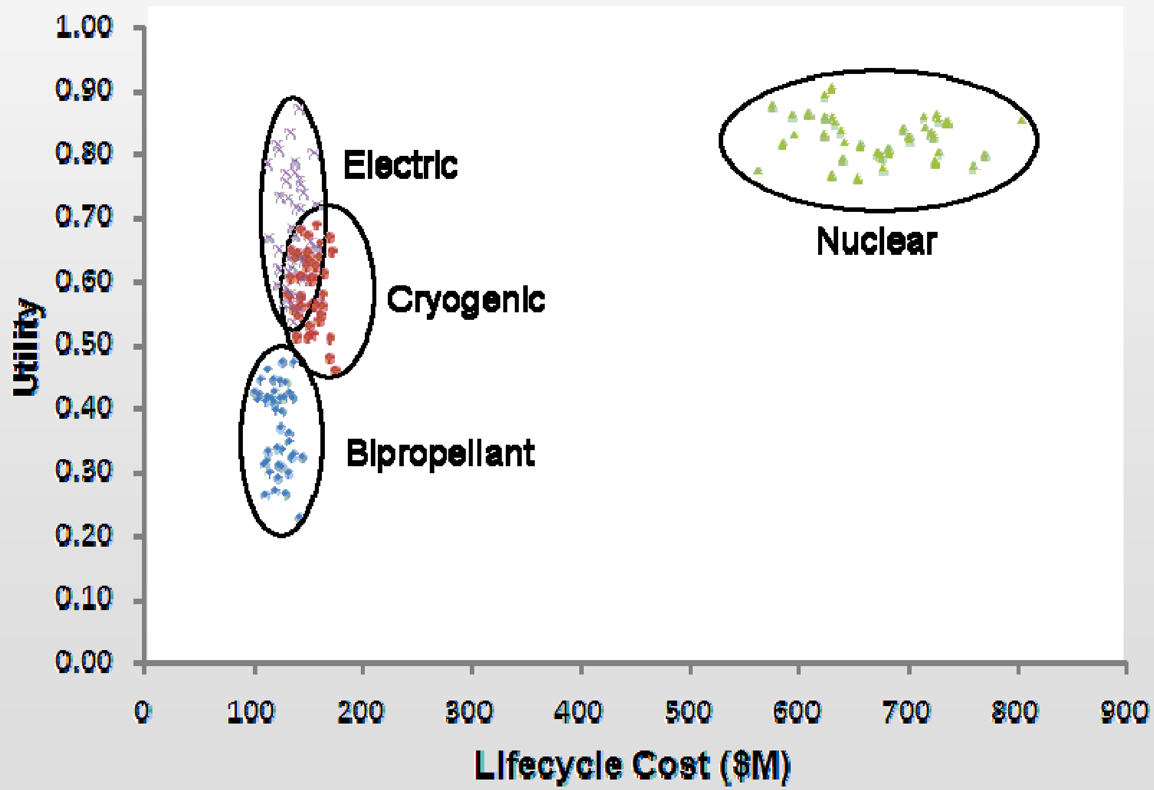
Cryo/bipropellant expendable



Electric cruiser

Monte Carlo Simulation

- MCS was used to introduce endogenous performance and cost uncertainties into the 4 designs highlighted by EEA
- Specific impulse, mass fraction, delta-V, and cost were each sampled 40 times from rectangular distributions



Grappling with Uncertainty Quantification and Analysis

- Many methods exist for characterizing, quantifying, and analyzing uncertainty (qualitative, semi-quant, full-quant)
- MCS (probability-based) and EEA (possibility, temporal-based) each address different aspects of “uncertainty”
- Since many engineering problems face both endogenous and exogenous uncertainties, the combination of both MCS and EEA or a hybrid method may offer more insight than either method alone
- In the end, the choice of a method must be directed by the nature of the uncertainty

When addressing uncertainty, communication of what is captured, how it is captured, and how these factors arise and interact is almost as important as the analysis result itself, especially when the uncertainties are not well characterized

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Thank you!

Questions?