SEAri Short Course Series

Course: PI.27s Value-driven Tradespace Exploration for System Design

Lecture: Lecture 9: Uncertainty and Risk

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[PI.27s] Value-Driven Tradespace Exploration for System Design

Lecture 9
Uncertainty and Risk

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Outline

- Importance of managing uncertainty
- Motivations and sources of uncertainty
- Framework for considering uncertainties
- Implications for tradespace exploration
  - Using portfolios as a risk mitigation technique
  - Space Tug example
- Methods for TSE in Uncertain Environment
  - Space Tug example

FRAMEWORK CONCEPTS IN THIS MODULE ADAPTED FROM: McManus, H. and Hastings, D.E., "A Framework for Understanding Uncertainty and Its Mitigation and Exploitation in Complex Systems," *IEEE Engineering Management Review*, Vol. 34, No. 3, pp. 81-94, Third Quarter 2006

REFERENCE FOR MONTE CARLO SIMULATION: Rader, A., Ross, A.M. and Rhodes, D.H., A Methodological Comparison of Monte Carlo Simulation and Epoch-Era Analysis for Tradespace Exploration in an Uncertain Environment, IEEE Systems Conference, April 2010

Importance of Managing Uncertainty

- Growing body of work on uncertainty
  - Conventional (technical) uncertainties
  - Market and strategic environment
  - Budget and policy decisions
  - Management and team dynamics

Need unified approach for effectively dealing with uncertainty

- Awareness of need for advanced “attributes”
  - Robust, flexible, evolutionary systems called for
  - Confusion about what these terms mean

- New tools for addressing uncertainty
  - Tradespace analysis
  - Design strategies (e.g., modularity)
  - Real options and portfolio theory

Motivation for Effective Uncertainty Management

Biggest risks *and greatest opportunities* result from….

- changes in user needs
- changes in system contexts
- changes in interfaces (definition and/or allocation)
- changes in constituents in SoS (trigger for complex interface changes and enterprise uncertainties)

Sources of Uncertainty

Development and Model Uncertainty

Development uncertainty: Uncertainties of development of a product/service

- Political uncertainty - Development funding stability
- Requirements uncertainty - Requirements stability
- Development cost uncertainty - Development within cost targets
- Development schedule uncertainty - Development within schedule targets
- Development technology uncertainty - Technology provides expected performance

Model uncertainty: Uncertainties in system tools/models

Sources of Uncertainty

Operational Uncertainty

Operational uncertainty: Uncertainties of contributing value once product/service is developed

- Political uncertainty - Operational funding stability
- Market Uncertainty - Meet demands of uncertain market
- Lifetime uncertainty - Performing to requirements for life
- Obsolescence uncertainty - Performing to evolving expectations
- Integration uncertainty - Operating within other systems
- Operations cost uncertainty - Meeting operations cost targets

A Framework for Uncertainty Discussions

Uncertainties	Risks/ Opportunities	Mitigations/ Exploitations	Outcomes
Things that are not known or are known imprecisely	*Pathologies (probability x impact) or opportunities created by uncertainties*	*Mitigations are approaches to minimize risk. Exploitations are approaches to value creation.*	*Attributes a system user will find valuable*

<Uncertainty> causes <Risk/Opportunity> handled by <Mitigation/Exploitation> resulting in <Outcome>

A Framework for Discussion

Uncertainties	Risks/ Opportunities	Mitigations/ Exploitations	Outcomes
• Lack of Knowledge • Lack of Definition • Statistically Characterized Variables • Known Unknowns • Unknown Unknowns	• Disaster • Failure • Degradation • Cost/Schedule (+/-) • Market shifts (+/-) • Need shifts (+/-) • Extra Capacity • Emergent Capabilities	• Margins • Redundancy • Design Choices • Verification and Test • Generality • Upgradeability • Modularity • Tradespace Exploration • Portfolios&Real Options	• Reliability • Robustness • Versatility • Changeability • Evolvability • Interoperability

<Uncertainty> causes <Risk/Opportunity> handled by <Mitigation/Exploitation> resulting in <Outcome>

A Framework for Discussion

Uncertainties

- Lack of Knowledge
- Lack of Definition
- Statistically Characterized Variables
- Known Unknowns
- Unknown Unknowns

Risks/ Opportunities

- Disaster
- Failure
- Degradation
- Cost/Schedule (+/-)
- Market shifts (+/-)
- Need shifts (+/-)
- Extra Capacity
- Emergent Capabilities

Mitigations/ Exploitations

- Margins
- Redundancy
- Design Choices
- Verification and Test
- Generality
- Upgradeability
- Modularity
- Tradespace Exploration
- Portfolios&Real Options

Outcomes

- Reliability
- Robustness
- Versatility
- Changeability
- Evolvability
- Interoperability

<Uncertainty> causes <Risk/Opportunity> handled by <Mitigation/Exploitation> resulting in <Outcome>

Uncertainties

Lack of Knowledge	Facts that are not known or are known imprecisely that are needed to complete the system architecture
Lack of Definition	Things about the system that have not yet been specified or decided
Statistical Variables	Things that cannot always be precisely known but that can be statistically characterized or bounded (e.g., weather)
Known Unknowns	Things that are known that are not known (with time and effort will be)
Unknown Unknowns	By definition, are not known

Risks/Opportunities

Disaster	System causes harm
Failure/ emergent capabilities	System does not work/works in unexpected ways or for purposes not originally envisioned
Degradation/ unexpected capacity	System works but not up to initial expectations/ exceeds initial expectations
Funding, cost or schedule deviation	Program to produce system, gets into various trouble, or is conversely early or under budget
Market Shifts	System works but need for its services has changed from assumed level (+ or -)
Need Shifts	System works, but function desired from system has changed from what designed for (+ or -)

A Framework for Discussion

Uncertainties

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- Unknown Unknowns

Risks/ Opportunities

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<Uncertainty> causes <Risk/Opportunity> handled by <Mitigation/Exploitation> resulting in <Outcome>

Current Techniques: Risk Analysis

Uncertainties

- Lack of Knowledge
- Lack of Definition
- Statistically Characterized Variables
- Known Unknowns
- Unknown Unknowns

Risks/ Opportunities

- Disaster
- Failure
- Degradation
- Cost/Schedule (+/-)
- Market shifts (+/-)
- Need shifts (+/-)
- Extra Capacity
- Emergent Capabilities

Mitigations/ Exploitations

- Margins
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Outcomes

- Reliability
- Robustness
- Versatility
- Changeability
- Evolvability
- Interoperability

- Characterize small (but finite) risks with large hazards associated
- How these can be reduced by system design may be appropriate tradespace exploration question

Systems Engineering Advancement Research Initiative

A Framework for Discussion

Uncertainties

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- Unknown Unknowns

Risks/ Opportunities

- Disaster
- Failure
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- Cost/Schedule (+/-)
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Mitigations/ Exploitations

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Outcomes

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<Uncertainty> causes <Risk/Opportunity> handled by <Mitigation/Exploitation> resulting in <Outcome>

Mitigations/Exploitations (1 of 2)

Margins	Designing systems to be more capable to withstand worse environments, and to last longer than 'necessary'
Redundancy	Multiple copies of subsystems (or entire system) to assure at least one works
Design Choices	Choosing design strategies, technologies, and or subsystems that are not vulnerable to known risk
Verification & Test	Testing to drive out known variations, bound known unknowns, surface unknown unknowns
Generality	Using multi-function (sub) systems and interfaces rather than specialized ones
Serviceability/ Upgradeability	(Sub) systems that can be modified to improve or change function

Mitigations/Exploitations (2 of 2)

Modularity, Open Architectures and Standard Interface	Functions grouped into modules and connected by standard interfaces in such as way that they can “plug and play”
Tradespace Exploration	Analyzing or simulating many possible solutions under many possible conditions
Portfolio or Real Options	Emerging techniques originating in the financial world allowing strategies as information is available or markets change

A Framework for Discussion

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Mitigations/ Exploitations

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Outcomes

- Reliability
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- Interoperability

<Uncertainty> causes <Risk/Opportunity> handled by <Mitigation/Exploitation> resulting in <Outcome>

Outcomes

Reliability	*Probability that the system will do the job it was asked to do (i.e. will work).*
Robustness	*Ability of a system to maintain its level and set of specification parameters in the context of changing system external and internal forces*
Versatility	*Ability of a system to satisfy diverse expectations on the system without the need for changing form*
Changeability	*Ability of a system to be changed by an external or internal change agent*
Evolvability	*Ability of the system to serve as the basis of new systems (or new generations of the current system) to meet new needs and/or attain new capability levels.*

Current Techniques IN the Tradespace: Margins

Uncertainties

- Lack of Knowledge
- Lack of Definition
- Statistically Characterized Variables
- Known Unknowns
- Unknown Unknowns

Risks/ Opportunities

- Disaster
- Failure
- Degradation
- Cost/Schedule (+/-)
- Market shifts (+/-)
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- Extra Capacity
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Mitigations/ Exploitations

- Margins
- Redundancy
- Design Choices
- Verification and Test
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Outcomes

- Reliability
- Robustness
- Versatility
- Changeability
- Evolvability
- Interoperability

- Ubiquitous use of margins in early design
- Mostly experienced based; some work on probabilistic basis (Thunnissen 2004, probabilistic design)
- ***In tradespace analysis, need to get these right***

Current Techniques IN the Tradespace: Reliability Engineering

Uncertainties	Risks/ Opportunities	Mitigations/ Exploitations	Outcomes
• Lack of Knowledge	• Disaster	• Margins	• Reliability
• Lack of Definition	• Failure	• Redundancy	• Robustness
• Statistically Characterized Variables	• Degradation	• Design Choices	• Versatility
• Known Unknowns	• Cost/Schedule (+/-)	• Verification and Test	• Changeability
• Unknown Unknowns	• Market shifts (+/-)	• Generality	• Evolvability
	• Need shifts (+/-)	• Upgradeability	• Interoperability
	• Extra Capacity	• Modularity	
	• Emergent Capabilities	• Tradespace Exploration	
		• Portfolios&Real Options	

- At MATE level, not much to work with (definition too coarse)
- Data sparse, must make assumptions/approximations

Current State of Practice: Risk Management

Uncertainties	Risks/ Opportunities	Mitigations/ Exploitations	Outcomes
• Lack of Knowledge	• Disaster	• Margins	• Reliability
• Lack of Definition	• Failure	• Redundancy	• Robustness
• Statistically Characterized Variables	• Degradation	• Design Choices	• Versatility
• Known Unknowns	• Cost/Schedule (+/-)	• Verification and Test	• Changeability
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	• Need shifts (+/-)	• Upgradeability	• Interoperability
	• Extra Capacity	• Modularity	
	• Emergent Capabilities	• Tradespace Exploration	
		• Portfolios&Real Options	

- Current SOP is experienced based, not very effective (!)
- Only Known Unknowns (and only a subset of these) considered

Uncertainty Management Implied in Traditional Systems Engineering

Uncertainties

- Lack of Knowledge
- Lack of Definition
- Statistically Characterized Variables
- Known Unknowns
- Unknown Unknowns

Risks/ Opportunities

- Disaster
- Failure
- Degradation
- Cost/Schedule (+/-)
- Market shifts (+/-)
- Need shifts (+/-)
- Extra Capacity
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Mitigations/ Exploitations

- Margins
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Outcomes

- Reliability
- Robustness
- Versatility
- Changeability
- Evolvability
- Interoperability

- Test the heck out of it
- Expensive!
- Technical Downside only
- Outputs come late, not early, in the process

Exploring Uncertainty ON the Tradespace

Uncertainties	Risks/ Opportunities	Mitigations/ Exploitations	Outcomes
• Lack of Knowledge • Lack of Definition • Statistically Characterized Variables • Known Unknowns • Unknown Unknowns	• Disaster • Failure • Degradation • Cost/Schedule (+/-) • Market shifts (+/-) • Need shifts (+/-) • Extra Capacity • Emergent Capabilities	• Margins • Redundancy • Design Choices • Verification and Test • Generality • Upgradeability • Modularity • Tradespace Exploration • Portfolios&Real Options	• Reliability • Robustness • Versatility • Changeability • Evolvability • Interoperability

- A proposed alternative/supplement

Exploiting Uncertainty via Changeability

Uncertainties

- Lack of Knowledge
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- Known Unknowns
- Unknown Unknowns

Risks/ Opportunities

- Disaster
- Failure
- Degradation
- Cost/Schedule (+/-)
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Mitigations/ Exploitations

- Margins
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Outcomes

- Reliability
- Robustness
- Versatility
- Changeability
- Evolvability
- Interoperability

- Key to actively approaching “unknown unknowns”

Living in an Uncertain World: Evolutionary Acquisition

Uncertainties

- Lack of Knowledge
- Lack of Definition
- Statistically Characterized Variables
- Known Unknowns
- Unknown Unknowns

Risks/ Opportunities

- Disaster
- Failure
- Degradation
- Cost/Schedule (+/-)
- Market shifts (+/-)
- Need shifts (+/-)
- Extra Capacity
- Emergent Capabilities

Mitigations/ Exploitations

- Margins
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Outcomes

- Reliability
- Robustness
- Versatility
- Changeability
- Evolvability
- Interoperability

- Even if this generation of products cannot adapt, the next one can

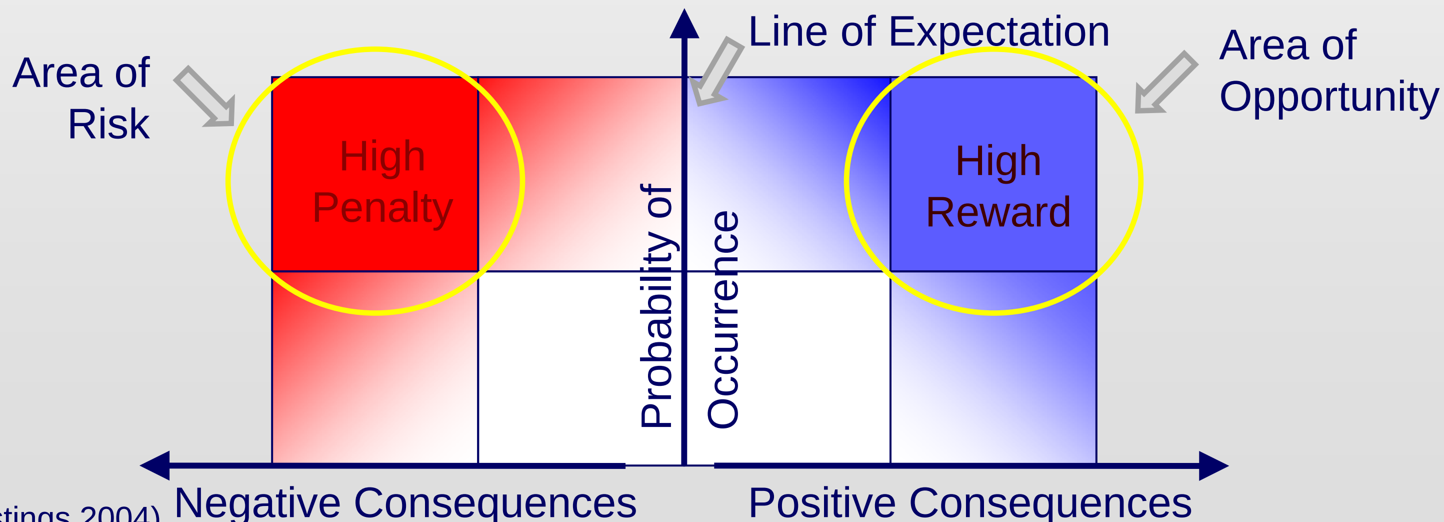
UPSIDE of Uncertainty: Advanced Desired Attributes

- **Reliability:** *Probability that the system will do the job it was asked to do (i.e. will work)*.
- **Robustness:** *Ability of a system to maintain its level and set of specification parameters in the context of changing system external and internal forces*
- **Versatility:** *Ability of a system to satisfy diverse expectations on the system without the need for changing form*
- **Changeability:** *Ability of a system to be changed by a system-external or system-internal change agent*
- **Evolvability:** *Ability of the system to serve as the basis of new systems (or new generations of the current system) to meet new needs and/or attain new capability levels.*

Much confusion in both terminology and real needs

Uncertainty in Design

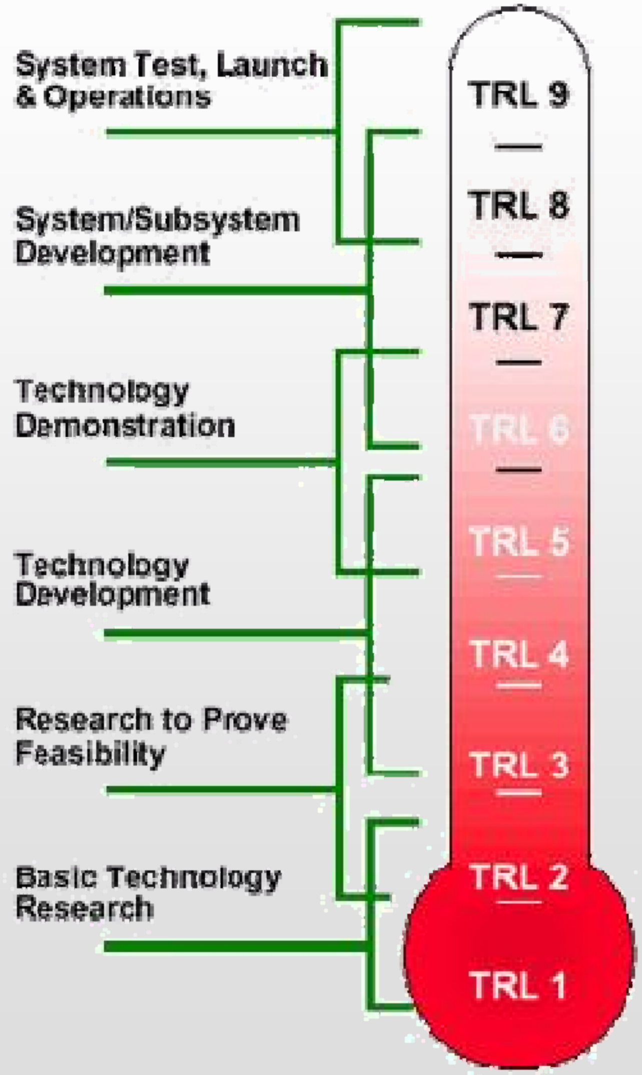
- Designers face exogenous & endogenous uncertainties
  - User requirements & constraints (exogenous)
  - Economic & political environment (exogenous)
  - Operational environment (exogenous)
  - Actual vs. expected/simulated performance; “model uncertainties” (endogenous)
- Uncertainty leads to both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



(Walton and Hastings 2004)

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)



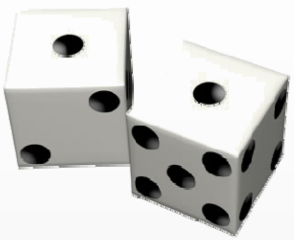
(Thornton 2004, NASA 2007)

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

↓

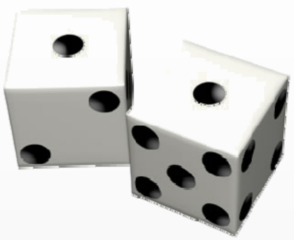
Calculate M values of ***each*** output variable using simulation model and each random sample

↓

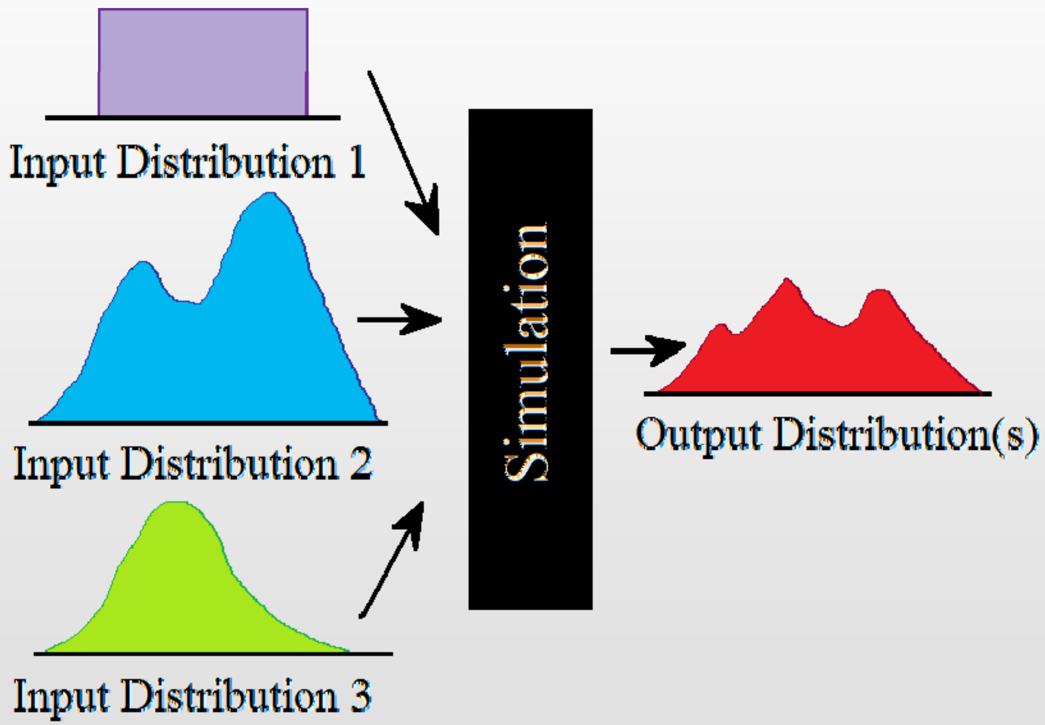
Plot resulting probability distribution(s) of output variables

Iterate as necessary to examine new input variables or distributions

Characteristics of Monte Carlo Simulation

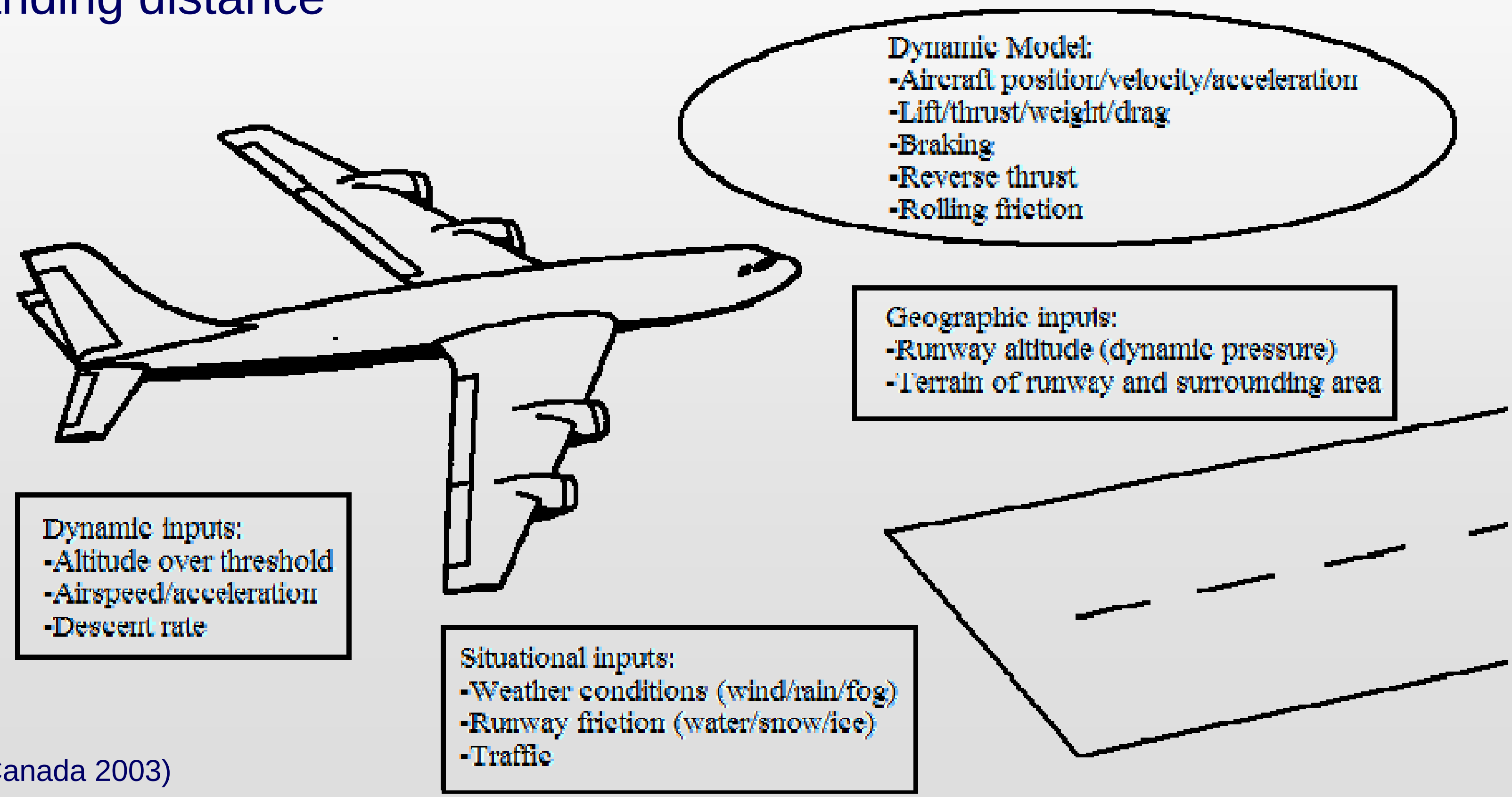


- Numerically formulated
- Wide range of types and applications
- Ideal for problems with a large number of uncertainties for which probability distributions can be estimated
- Results dependent on probability distributions and sampling



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



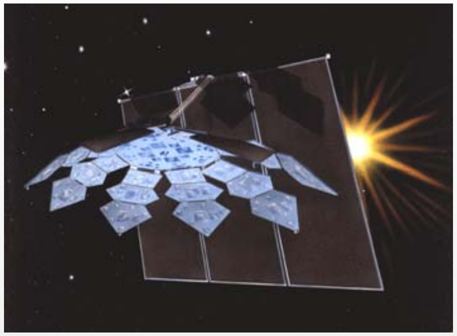
(Transport Canada 2003)

Tradespace Approaches

- Two methods for calculating the effects of uncertainties on the tradespace
  - Calculating extreme values
  - Monte Carlo
- Portfolio approaches to mitigating/exploiting uncertainties

Walton, M.A., *Managing Uncertainty in Space Systems Conceptual Design Using Portfolio Theory*, Doctor of Philosophy Dissertation, Aeronautics and Astronautics, MIT, June 2002

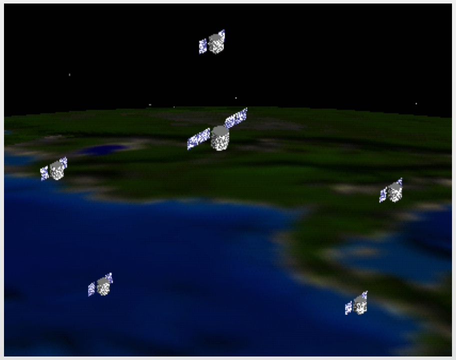
Description of Walton's Cases



Mission Name: Broadband System (Commercial)

Value Measure: Billable Hour/$

Uncertainty Measure: StdDev(BH/$)



Mission Name: A-TOS (Science)

Value Measure: Total Value*/$

Uncertainty Measure: StdDev(TV/$)

*Note Walton's work was pre-MATE, and "Value" was not rigorously defined
Does not affect value of work for exploring uncertainty mitigation

Example Uncertainty Sources from Broadband Case

Total Market Size

Market Capture

Discount Rate

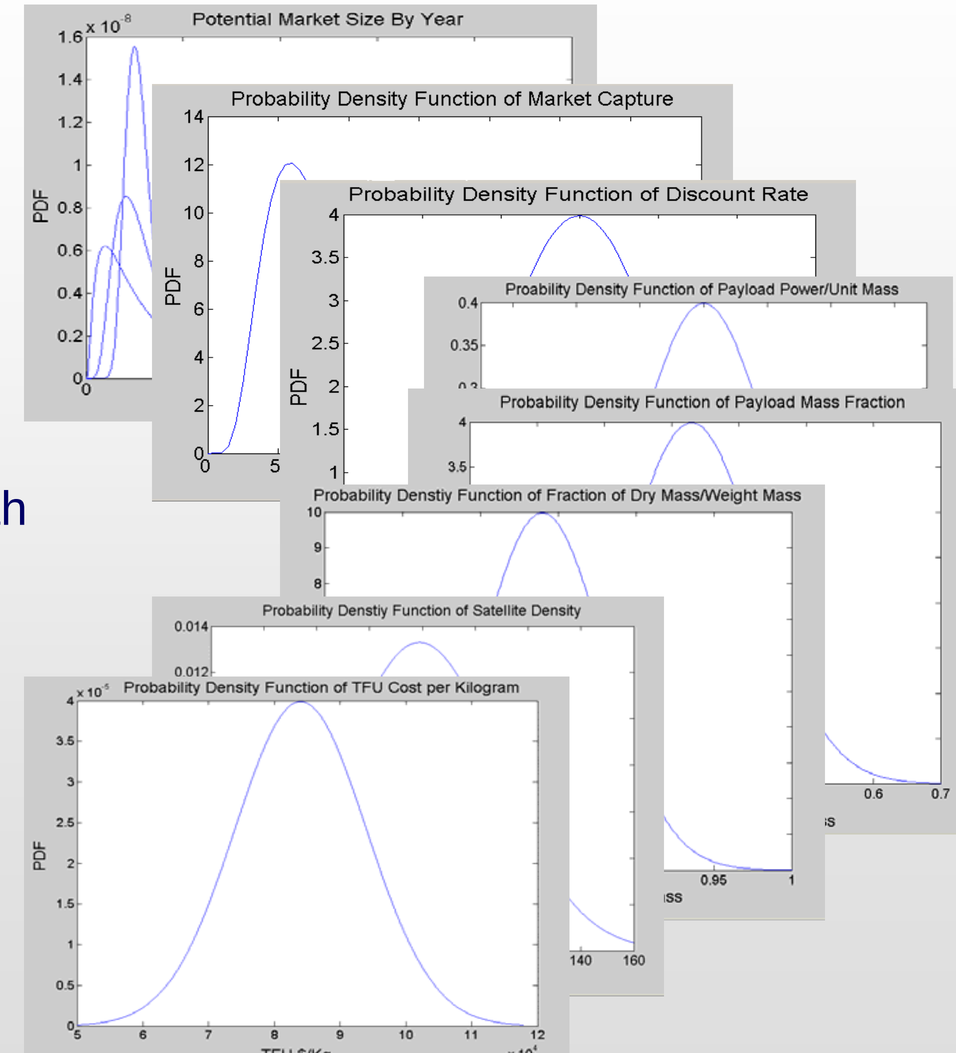
Payload Power per Unit Mass

Mass Fraction of the Payload with respect to Dry Mass

Fraction of Dry Mass

Density of Satellite

Theoretical First Unit Cost per Kilogram



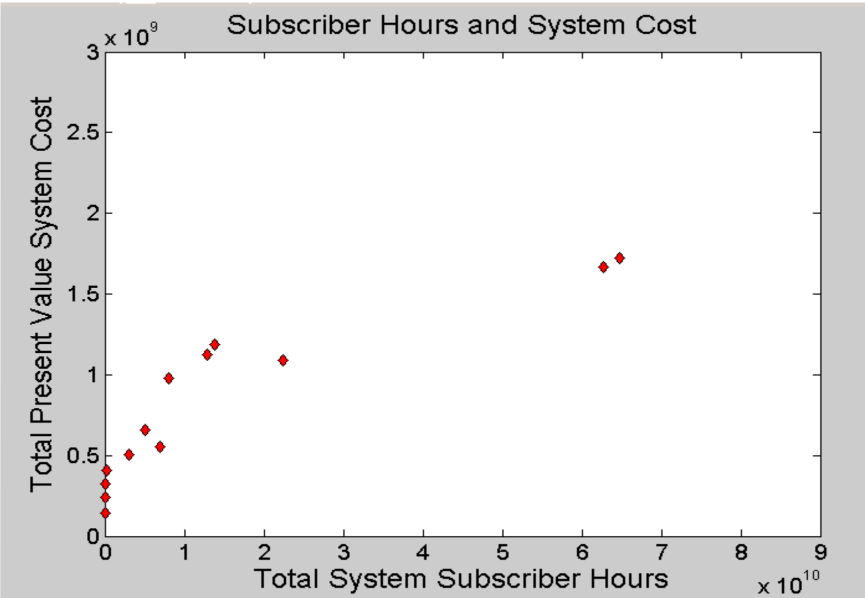
Data on sources comes from regression, testing, organizational and expert knowledge

Two Techniques to Quantify Embedded Architectural Uncertainty

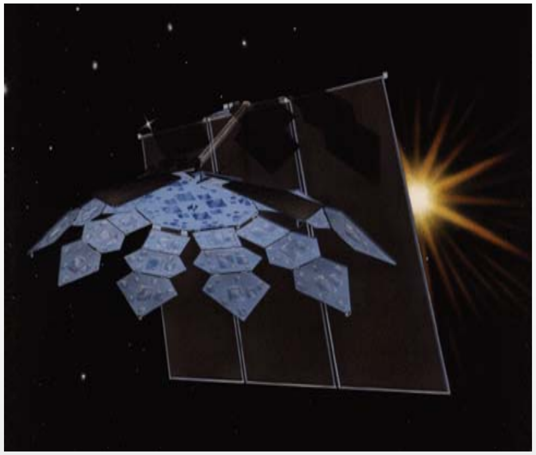
- Extreme Approach
  - Identify Best, Worst and Most Likely Cases for Uncertainty Sources
  - Produces three outputs for each architecture in the tradespace
  - Provides quick check for architecture sensitivities
- Monte Carlo Simulation Approach
  - Develop distributions for each source of uncertainty
  - For a given run, sample the uncertainty distributions
  - Hold uncertainties constant for enumeration of tradespace
  - Generate a single distribution datum for each architecture in the tradespace
  - Resample the sources of uncertainty and repeat
  - Allows for capture of higher moments, even if not incorporated into the portfolio theory analysis
  - Used in Broadband and A-TOS Cases

Extreme approach provides quick check on sensitivities,
Monte Carlo approach provides higher precision with more computation

Example: Broadband Satellite System



[P-Opt Set Calculated by Jilla, 2002]

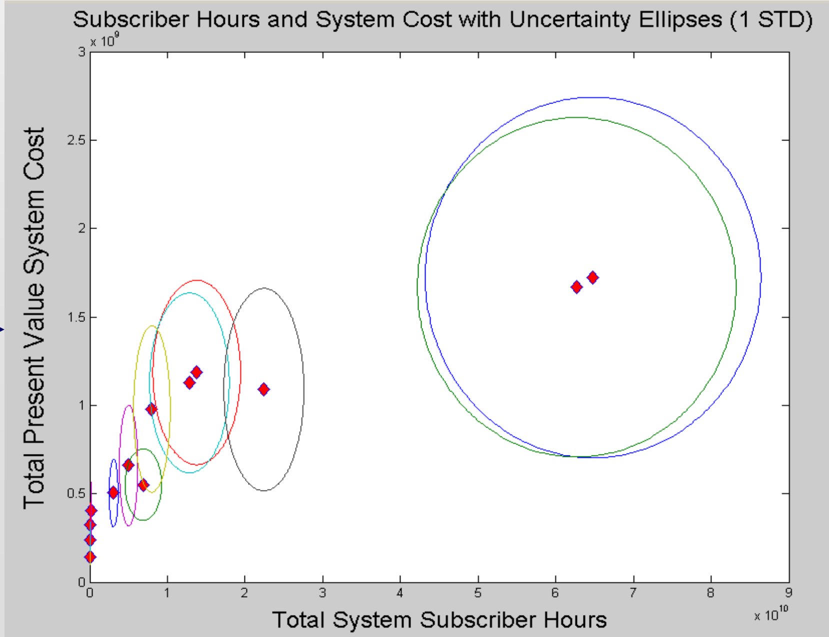


Design Vector

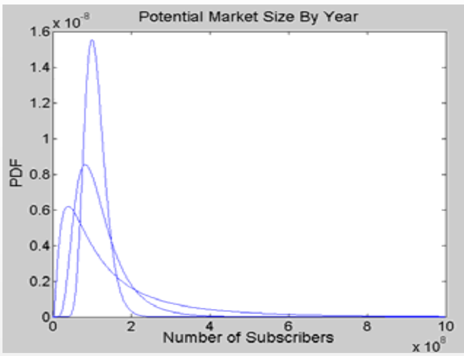
- ***# Satellites***
- ***Leo, Meo, Geo***
- ***Inclination***
- ***# Planes***
- ***Power***
- ***Ant Area***

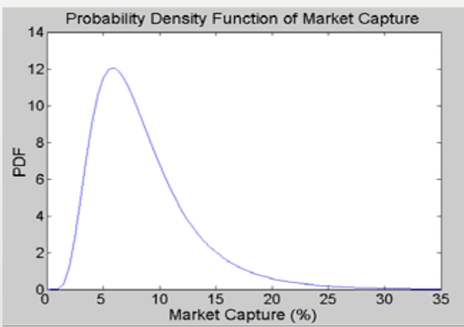
Sources of uncertainty:

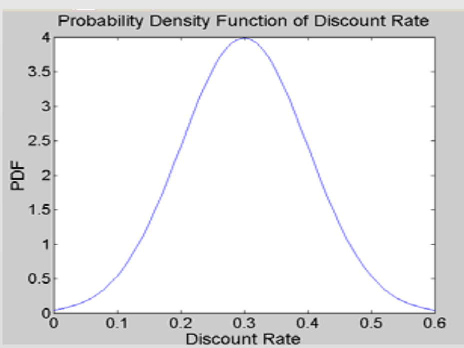
- **Total market size/yr**
- **Market capture**
- **Payload power/kg**
- **Mass fraction of payload/dry mass**
- **Fraction of dry mass in wetmass**
- **Density of satellite**
- **Discount rate**
- **TFCU/kg**

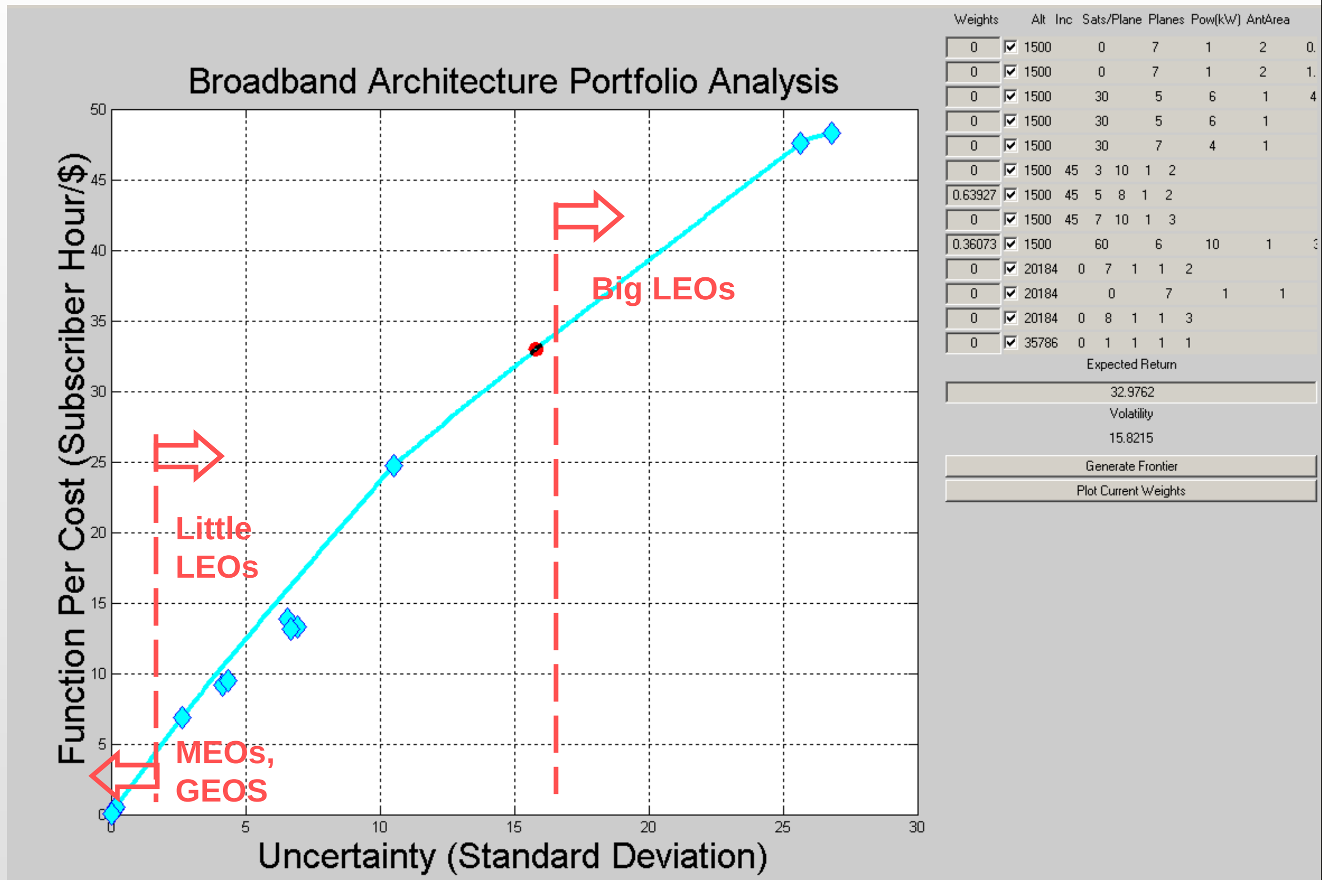


Broadband Uncertainty/Value Tradespace





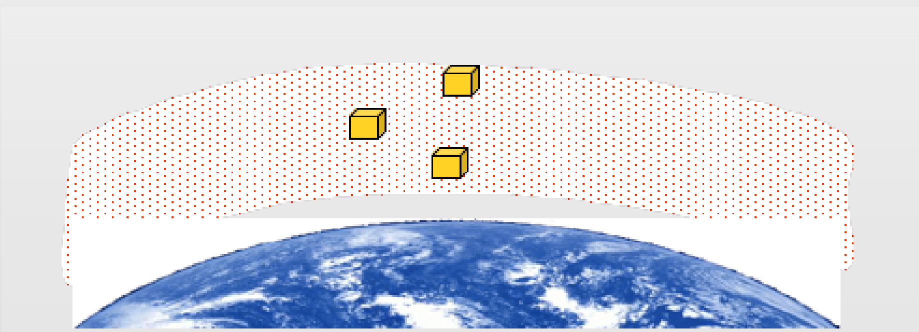




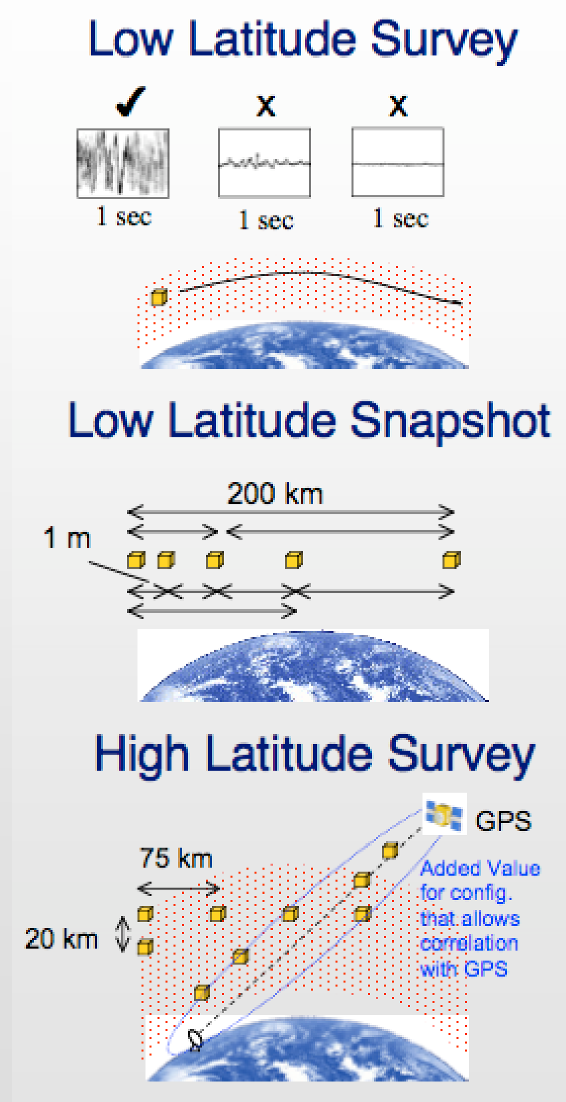
Risks are strongly correlated, portfolio does little better than best good single systems

A-TOS Example

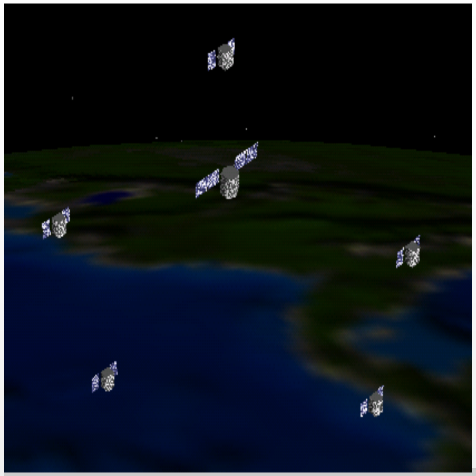
- Multi-mission system
- In-situ sensing of ionosphere
- Identical sets of existing instruments on all vehicles
- Swarm based architectures
- Non-rigorous “value” performance criteria



Small LEO Distributed Space System

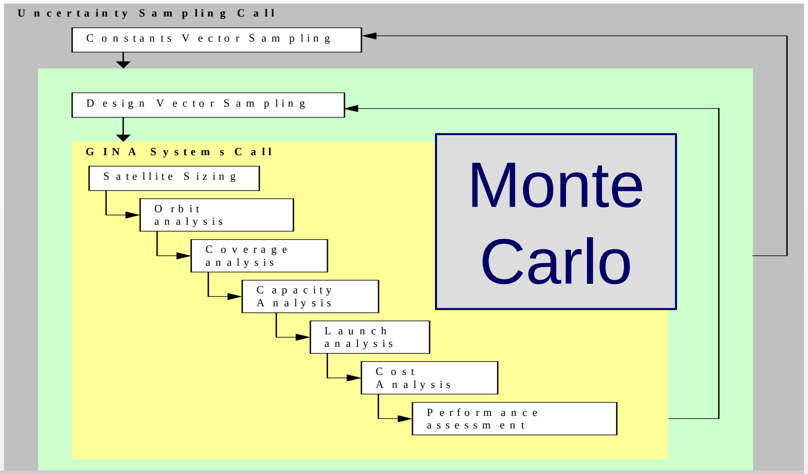


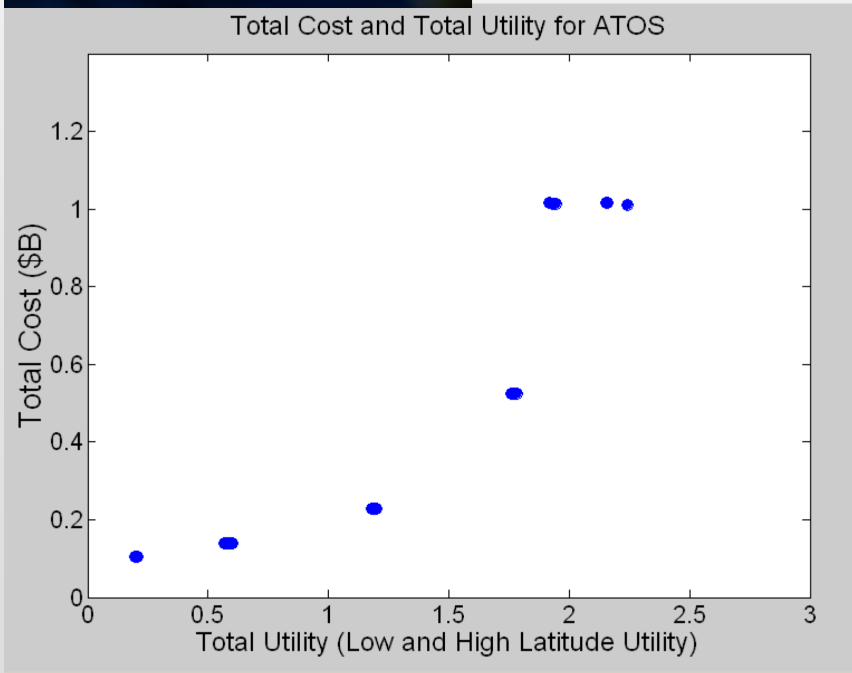
Capturing Uncertainty: A-TOS

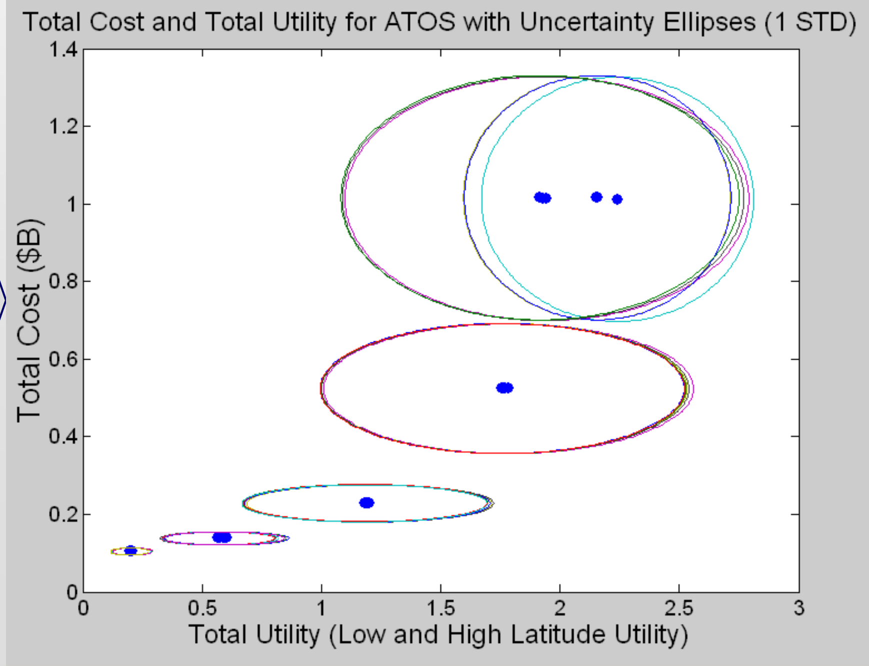


Uncertainty Sources

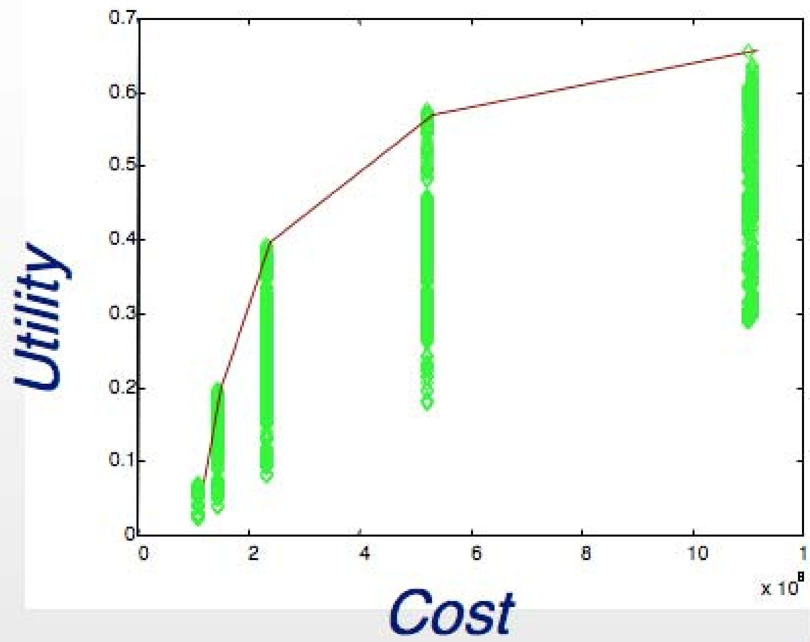
- MTTF for Sat
- CER for Sat Bus
- Payload Cost
- Operations Cost
- Low to High Mission Utility Value
- Satellite Density Sizing Ratio



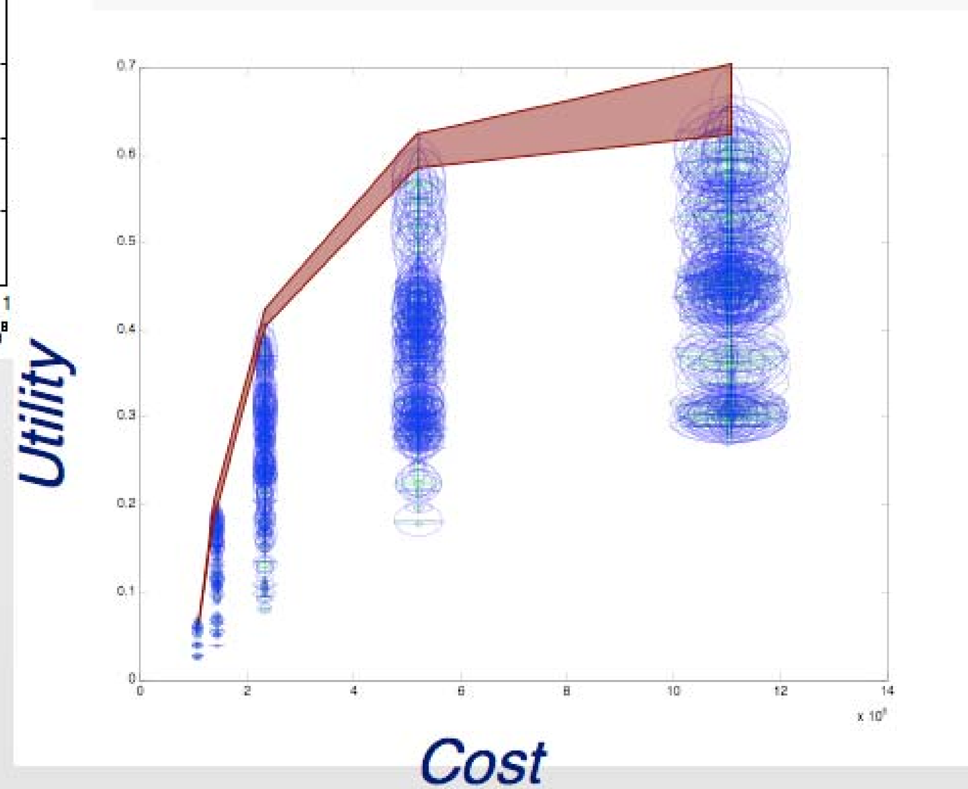




The "Fuzzy" Pareto Optimal Front



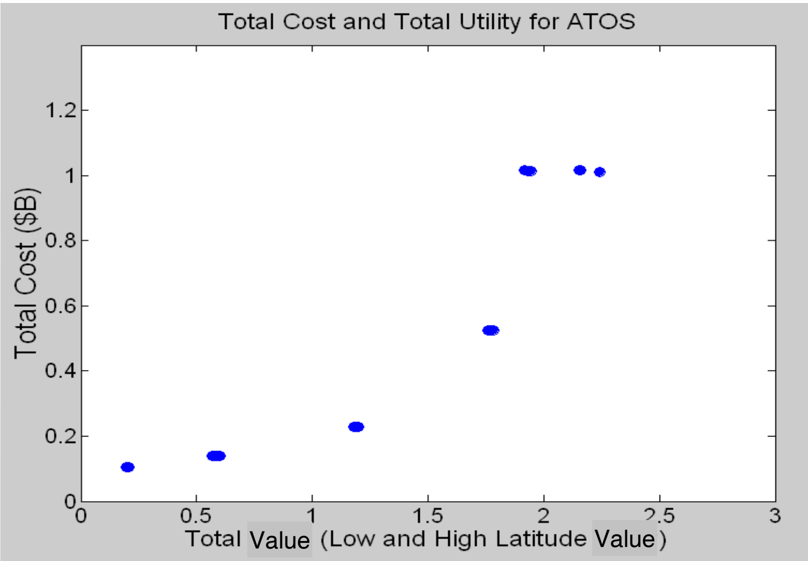
Concept of a simple front on which all attention is placed is questionable

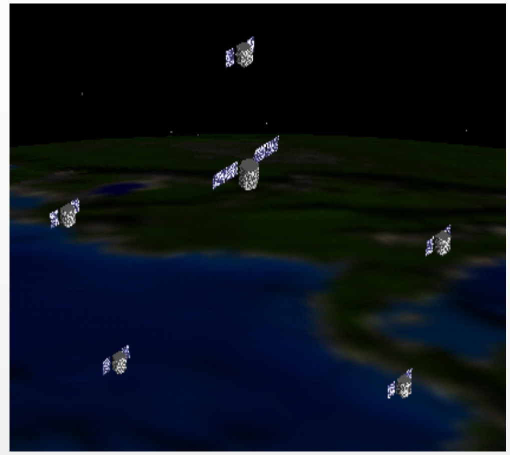


(Smaling 2005 discusses "fuzzy pareto optimality")

A-TOS Uncertainty Studies

Selected Designs





Design Vector

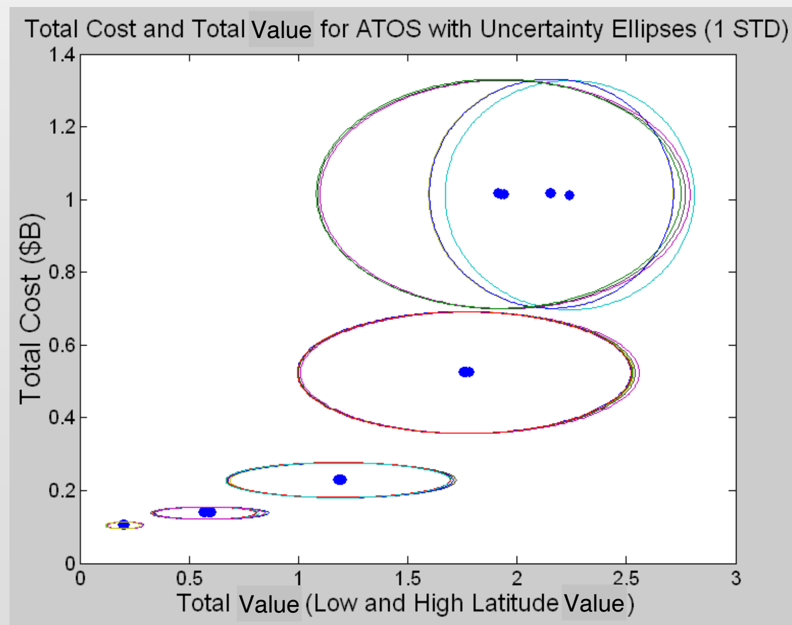
- ***# Satellites***
- ***Altitude***
- ***Subplanes/Swarm***
- ***Suborbits/Swarm***
- ***Subplane Yaw***
- ***Separation Distance***

Sources of uncertainty*:

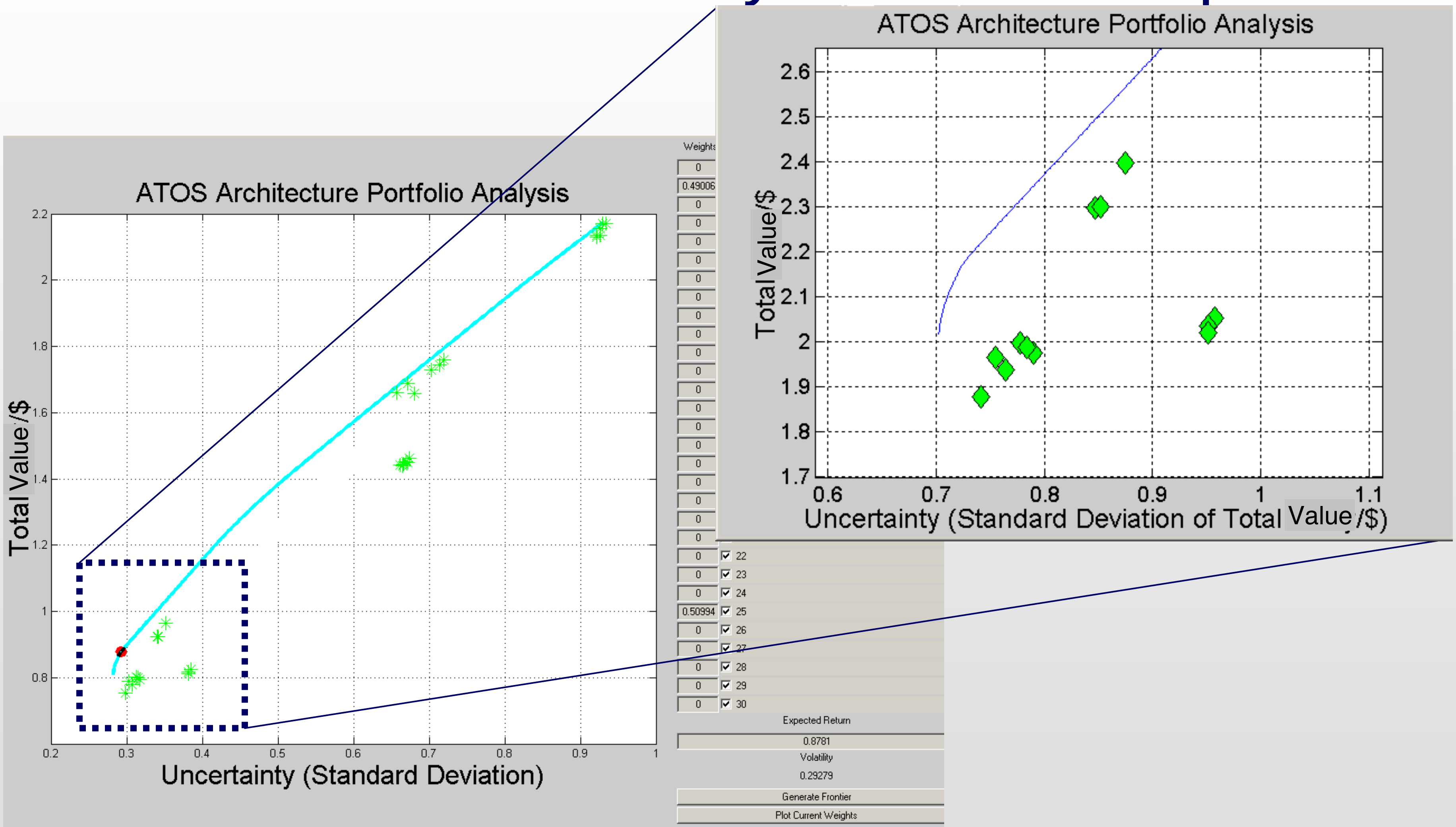
- ***MTTF for Sat***
- ***CER for Sat Bus***
- ***Payload Cost Unc***
- ***Operations Cost Unc***
- ***Low to High Mission Value***
- ***Satellite Density Sizing Ratio***

*Each source has uncertainty distribution

Monte Carlo



A-TOS Uncertainty/Value Tradespace



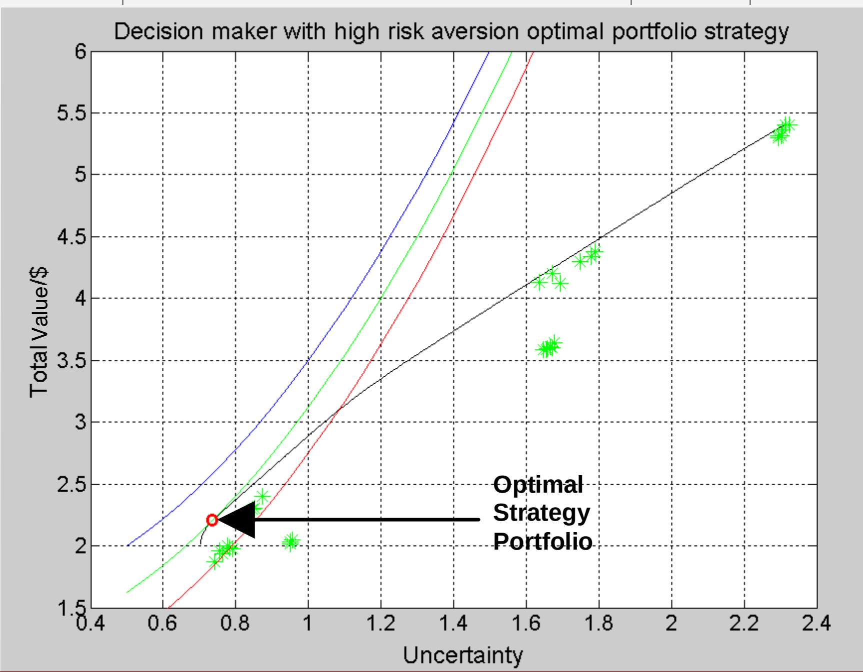
Efficient frontier extends beyond any single asset!

Systems Engineering Advancement Research Initiative

A-TOS
Two Decision Maker's Portfolios

High Risk Aversion Decision Maker

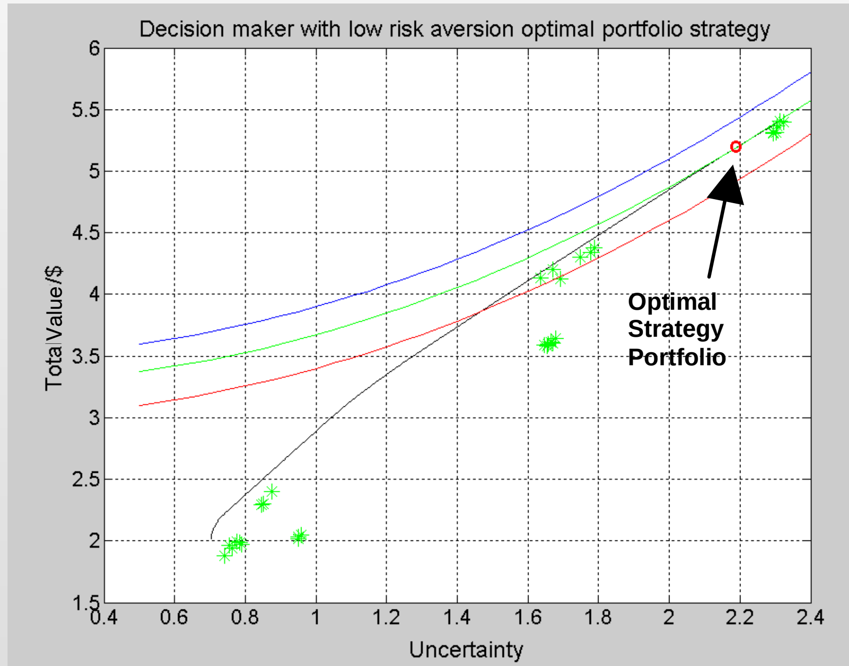
Percentage of Portfolio	Architecture Design Vector {sats/swarm, suborbs,size,yaw,subplanes,alt}	Total Value /$	Uncertainty
52%	{26,4,14.1,60,2,700}	2.4	0.9
48%	{2,1,3.8,30,1,300}	1.9	0.8
100%	Portfolio Value and Uncertainty	2.2	0.7



Uncertainty in the High Risk Aversion Portfolio is less than each of its assets

Low Risk Aversion Decision Maker

Percentage of Portfolio	Architecture Design Vector {sats/swarm, suborbs,size,yaw,subplanes,alt}	Total Value /$	Uncertainty
83%	{8,4,14.1,30,1,700}	5.4	2.3
17%	{4,2,3.8,30,1,500}	4.2	1.7
100%	Portfolio Value and Uncertainty	5.2	2.2

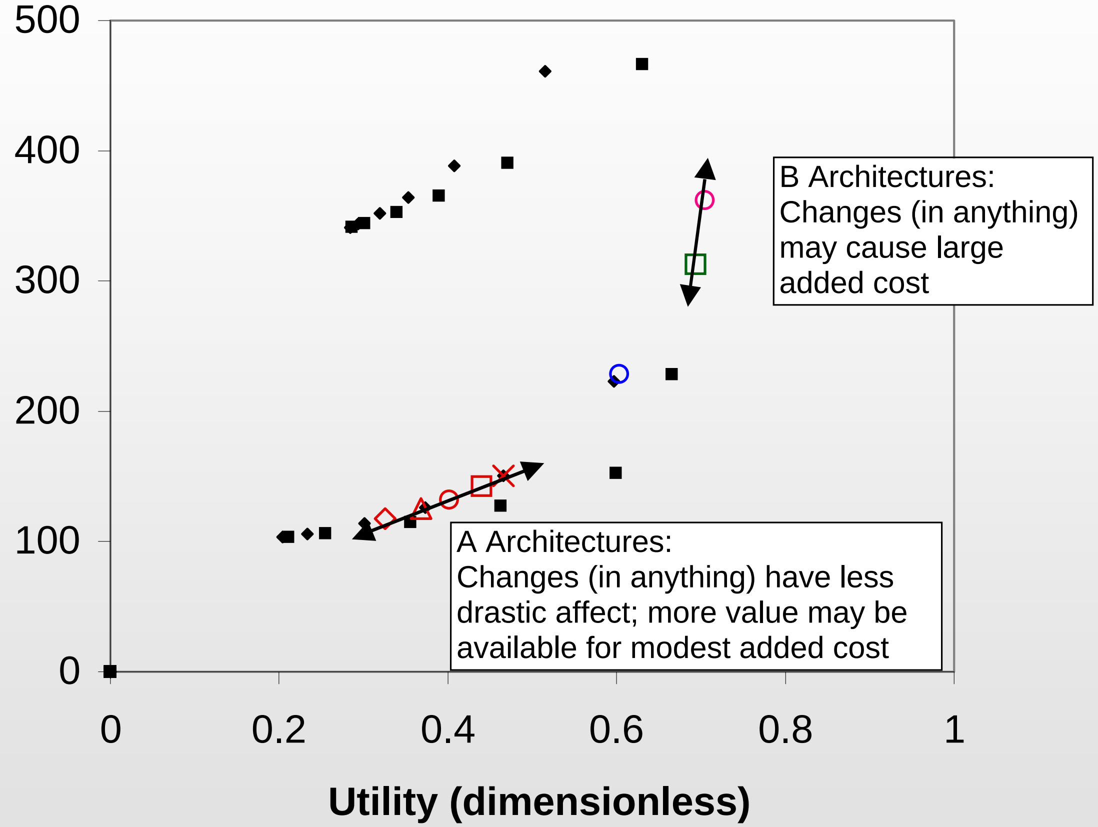


Low Risk Aversion Portfolio contains highest return design (i.e. highest TV/$)

Space Tug Example

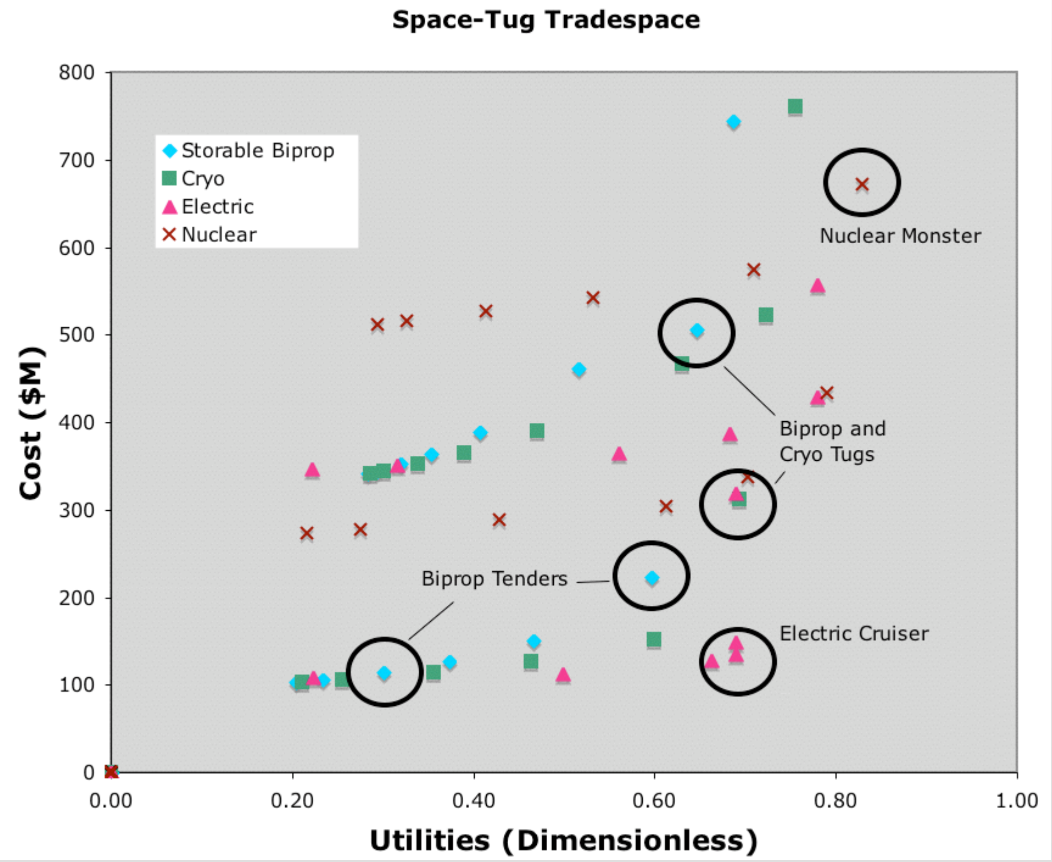
- An example of using the framework and a Monte Carlo analysis to:
  - Understand the precision of the tradespace
  - Identify risks
  - Identify opportunities
  - Explore ways of valuing the exploitation of uncertain opportunities

Direct Use of Tradespace Exploration



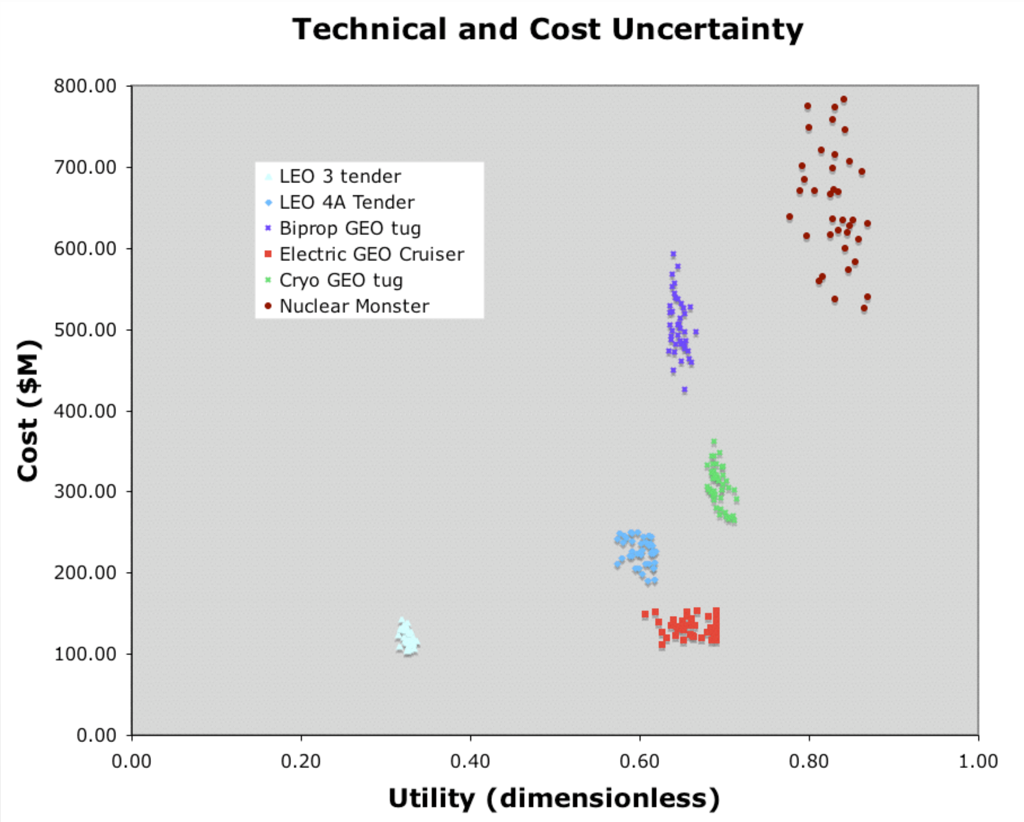
- Look at thousands of architectures with simulation models
- Often learn a lot by simple examination

Tradespace Analysis with Uncertainty



- MATE Space tug tradespace
- Pick subset for Monte Carlo analysis
- *Do not* concentrate on the Pareto front
- Pick distinct classes of designs

Monte Carlo Study



Uncertainties:

- Propulsion system ISP
- Propulsion system Mass
- Bus Mass
- Dry Mass Cost
- Wet Mass Cost

- *Explicitly* look at sensitivity of candidates to uncertainties
- Monte Carlo model - vary uncertain parameters - look at effects on technical attributes and cost

Systems Engineering Advancement Research Initiative

Exploiting Uncertainty via Versatility and Changeability

Uncertainties

- Lack of Knowledge
- Lack of Definition
- Statistically Characterized Variables
- Known Unknowns
- Unknown Unknowns

Risks/ Opportunities

- Disaster
- Failure
- Degradation
- Cost/Schedule (+/-)
- Market shifts (+/-)
- Need shifts (+/-)
- Extra Capacity
- Emergent Capabilities

Mitigations/ Exploitations

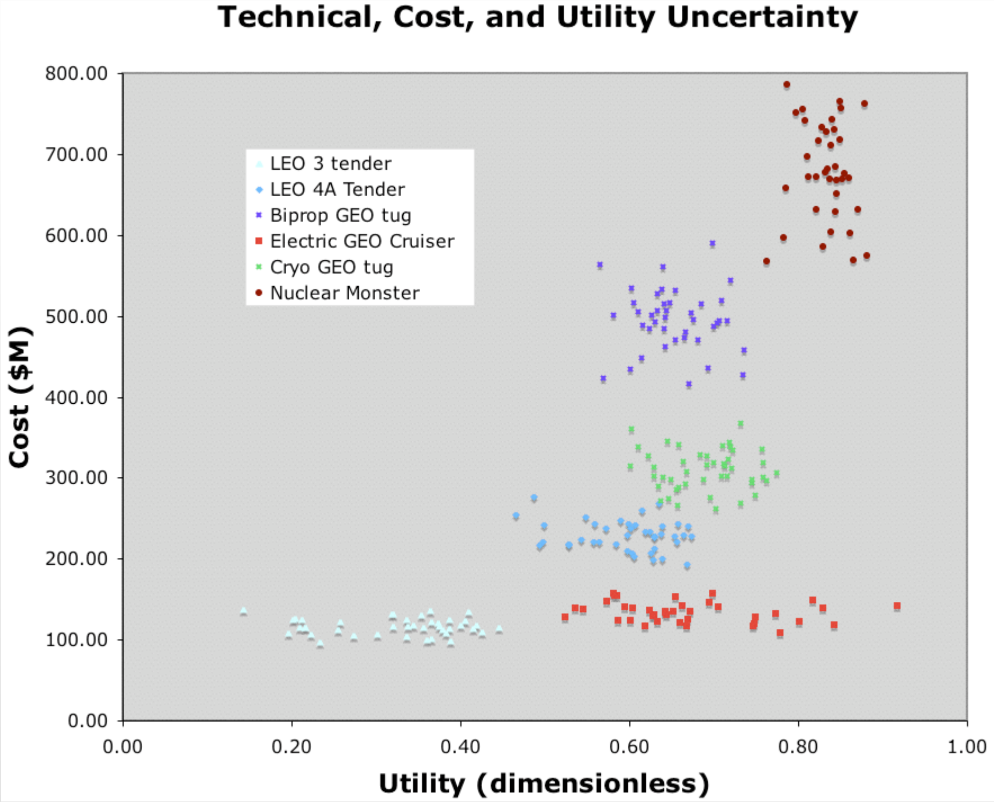
- Margins
- Redundancy
- Design Choices
- Verification and Test
- Generality
- Upgradeability
- Modularity
- Tradespace Exploration
- Portfolios&Real Options

Outcomes

- Reliability
- Robustness
- Versatility
- Changeability
- Evolvability
- Interoperability

- Key to actively approaching "unknown unknowns"

Add User Need Uncertainty



Uncertainties:

- Propulsion system ISP
- Propulsion system Mass
- Bus Mass
- Dry Mass Cost
- Wet Mass Cost
- **USER NEEDS**
- Delta-V, Speed, and Capability Utility & Weightings

- This is often the dominant uncertainty
- Increased user need creates *opportunity*

Summary

- Uncertainties of all types are present in front end design
- Risks *and opportunities* can be clarified using tradespace exploration:
  - Direct observation of tradespace
  - Best/worst case analysis
  - Monte-Carlo or other more complete method
  - Usually done on a subset; should NOT be just the “certain” Pareto set
- Under some circumstances, a portfolio approach may lower overall risks/maximize opportunities
  - Requires at least some un-correlated responses to uncertainties
- Biggest risk *and opportunity* result from changes in user needs, contexts, interfaces, and changes in SoS constituents

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