Aligning Perspectives and Methods for Value-Driven Design

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Outline

- Introduction
- Defining Value
- Economic Background
- Overview of VCDMs
- Spacecraft Mission Examples
- Discussion

Introduction

- What is the most valuable system for our mission?
  - Value is perceived by stakeholder(s) of interest
  - Value can be comprised of both direct and indirect benefits and costs
- Formulating a response: “valuation” methods
  - “Traditional” requirement- and cost-centric approaches
  - Value-driven design approaches
    - Theory: economics, decision analysis, psychology, behavioral economics, and complex engineering design
    - Operationalization: value-centric design methodologies (VCDMs)

Objective Domain

- Stakeholder Value
- Most Valuable System Design

Engineering Design Domain

- Candidate System Designs
- “Valuation” Method

- Relevancy: notable efforts in the aerospace sector
  - DARPA System F6 Program and valuation of fractionated spacecraft
    - Four industry-lead teams developed and applied VCDMs

Defining Value

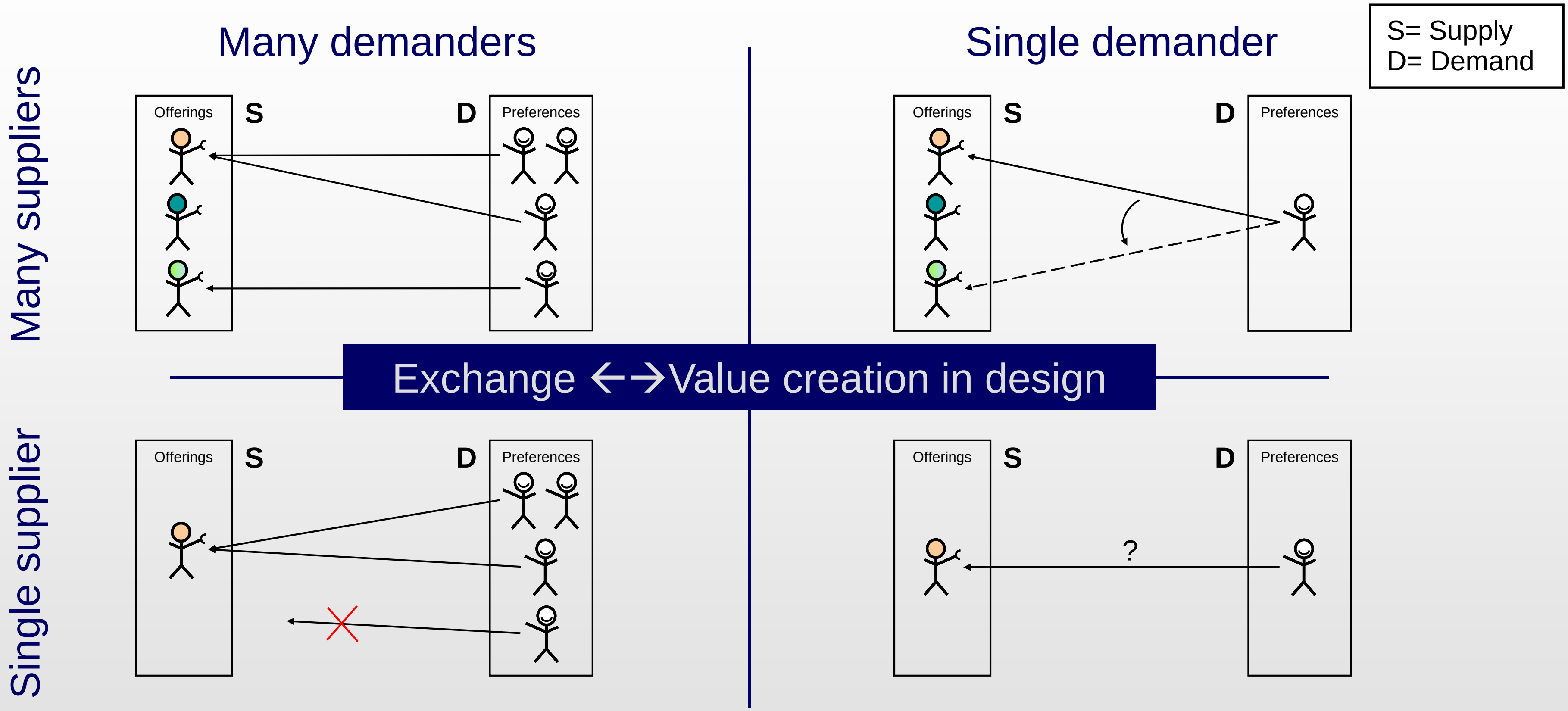
- “Value” definition includes several important factors
  - Cost/Resources
  - Satisfaction/Utility
  - Importance/Priority

Holistic definition of “creating value”
Balancing and increasing the net level of (1) satisfaction, with (2) available resources, while addressing (3) its degree of importance

- Value in design is subjective and context-dependent
  - Example: “value” of heated seats in Maine winter vs. Florida summer
- Evolution of definition in economic theory
  - Value in use vs. value in exchange
  - Scarcity vs. labor requirement
  - Willingness to pay (i.e., “price” vs. wealth)
  - Supply-side vs. demand-side
  - Marginal utility vs. marginal cost

Appropriate definition, partly dependent on the relevant “market” type and analysis perspective

Market “Types” and Value Creation



- In order for suppliers and demanders to experience “value” creation in system design, exchanges must occur
- Why does supplier participate? Why does demander?
- The smaller the market, the more the suppliers and demanders must understand “specifics” in order for “enough” exchanges to occur

Operationalizing in the Aerospace Context

- Several market types present in aerospace domain context
  - **Commercial** (e.g., communications) often more competitive market with many suppliers and many demanders (e.g., consumers)
  - **Defense/Intel** (e.g., aircraft, satellites) often more restricted markets with few suppliers and few (or single) demanders (e.g., governments)
  - **Science** (e.g., observatories) are often restricted markets with single suppliers and single demanders
- Depending on the "mission," the type of market will vary
- The market type can help guide an analyst on an appropriate operationalization of "value"
  - if "price" is well-defined (such as in commercial markets), then it can be used as a proxy for value in exchange
  - If "price" is not well-defined or inappropriate (such as in science markets), then an alternative to dollarization may be necessary

Depending on the mission, different market types may apply; the market type indicates appropriate metrics for value

Overview of VCDMs (1)

Various Value-Centric Design Methodologies (VCDMs) can be found in use for operationalizing value for design

- **Net Present Value**

$$NPV = D_o + \int_{t_j}^{t_k} \frac{D(t)}{(1+r(t))^t} dt \sim D_o + \sum_{t_j}^{t_k} \frac{D(t)}{(1+r(t))^t} \sim D_o + \sum_{t_j}^{t_k} \frac{D(t)}{(1+r)^t}$$

  - “Value”: discounted cash flow
  - Limitations: revenue-centric, forecasting, uncertainty, aggregation,…
- **Multi-Attribute Utility Theory** (with cost)

$$K \cdot U(\hat{X}) + 1 = \prod_{i=1}^{n} (K \cdot k_i \cdot U(X_i) + 1) \quad \text{where,} \quad K = -1 + \prod_{i=1}^{n} (K \cdot k_i + 1)$$

  - “Value”: aggregation of (non-monetary) benefits relative to monetary costs of achieving those benefits
  - Limitations: ordinality, aggregation, abstraction, independence,…

Overview of VCDMs (2)

- **Cost-Benefit Analysis**

$$CB = \left(\sum B_o - \sum C_o\right) + \left(\sum_{t_j}^{t_k} \frac{\sum B(t)}{(1+r)^t} - \sum_{t_j}^{t_k} \frac{\sum C(t)}{(1+r)^t}\right)$$

  - "Value": discounted monetary difference between set of monetized benefits and their monetized costs
  - Limitations: monetization, forecasting, uncertainty, distribution, …
- **Other** (see paper for details)
  - Cumulative Prospect Theory (CPT)
  - Value functions (VFs)
  - Analytical Hierarchy Process (AHP)
  - Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

This list is not complete; a multitude of valuation methods exist (e.g., from finance, economics, marketing, decision analysis, etc.)

Comparing Common VCDMs

Table can be used as guide to help choose appropriate VCDM

		A		B		C
Definition of Value	Value is discounted cash flow (monetized)		Value is discounted cash flow (monetized)		Value is an aggregation of a set of benefits relative to their respective net cost (non-monetized)	
Sources of Value	Value is not derived from any sources other than revenue		Value is derived from multiple benefits and costs		Value is derived from multiple benefits and costs	
Market Prediction	Cash flow and discount rate		Cash flow and discount rate			
	Extensive and quantitative predictions can be made about a system's future financial markets, revenue and pricing structures, demand functions, etc.		Extensive and quantitative predictions can be made about a system's future financial markets, revenue and pricing structures, demand functions, etc.			
Psycho-Economic	*Mutual additive (preferential) independence* – stakeholder(s) desirability for one system attribute value is entirely independent of the respective values of all other system attributes		*Mutual additive (preferential) independence* – stakeholder(s) absolute preference for a given attribute is independent of the respective values of all other system attributes		*Mutual utility independence* – stakeholder(s) relative preference between two values for a given attribute is independent of the respective values of all other attributes; absolute preference for one attribute is dependent on the respective values of all other attributes	
	Stationary assumption – stakeholder preferences do not change over time		*Stationary assumption* – stakeholder preferences do not change over time		*Stationary assumption* – stakeholder preferences do not change over time	
Stakeholder Perception	Multiple stakeholder preferences cannot be aggregated – nonexistence of a social welfare function		Multiple stakeholder preferences cannot be aggregated – nonexistence of a social welfare function		Multiple stakeholder preferences cannot be aggregated – nonexistence of a social welfare function	
	Stakeholder's make decision's under certainty – they have perfect foresight into all present and future events pertaining to the values of a system's attributes		Stakeholder's make decision's under certainty – they have perfect foresight into all present and future events pertaining to the values of a system's attributes		Stakeholders make decisions under uncertainty – they do not have perfect insight into all present and future events pertaining to the values of a system's attributes	
Calculating Value	Cash flow and/or discount rate are discrete in time and also potentially held as constants		Monetized benefits, costs, and/or discount rate are discrete in time and also potentially held as constants			
			Monetization of benefit(s)			
			Combine and normalize multiple benefits and costs into a single metric			
	Truncation of information regarding distribution of costs (monetized)		Truncation of the distribution of costs and benefits (monetized)		Truncation of the distribution of benefits into a single metric	
	Value is a cardinal metric		Value is a cardinal metric		Ordered comparison of benefit (non-ratio cardinal) and cost (cardinal) is assumed a proxy for value	
Tally	**Total Disagreements**		**Total Disagreements**		**Total Disagreements**	
VCDM	**Net Present Value (NPV)**		**Cost-Benefit Analysis (CBA)**		**Multiple Attribute Utility Theory (MAUT)**	

All VCDMs have limitations and inherent assumptions.
Goal should be thoughtful selection of most appropriate method.

Spacecraft Mission Examples

Telecommunications

Stakeholder: Satellite owner and service provider (e.g., DirecTV®, Inc.)

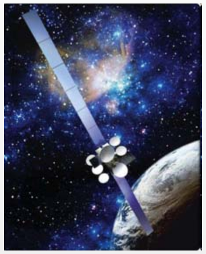


Photo: Boeing 702HP, http://www.boeing.com/defense-space/space/bss/factsheets/702/dtv10_11_12/dtv10_11_12.html

Telecommunications Mission

	Attribute	Definition	Units	Range (least to most desirable)
1	*Mission Lifetime*	Operational duration of spacecraft	years	[5, 15]
2	*Max Number of High Definition Channels*	Max number of distinct HD channels available for broadcast	-	[0, 100]
3	*Max Number of Standard Definition Channels*	Max number of distinct SD channels available for broadcast	-	[0, 200]
4	*Max Downlink Internet Bandwidth*	Max downlink internet bandwidth (aggregate)	Mbps	[0, 1080]
5	*Uplink Internet Bandwidth*	Max uplink internet bandwidth (aggregate)	Mbps	[0, 1080]

Value proposition: provide high quality broadband entertainment to subscribers in North America for at least five years using one satellite, while maximizing profit

Deep space

Stakeholder: Civil science agency (e.g., NASA)

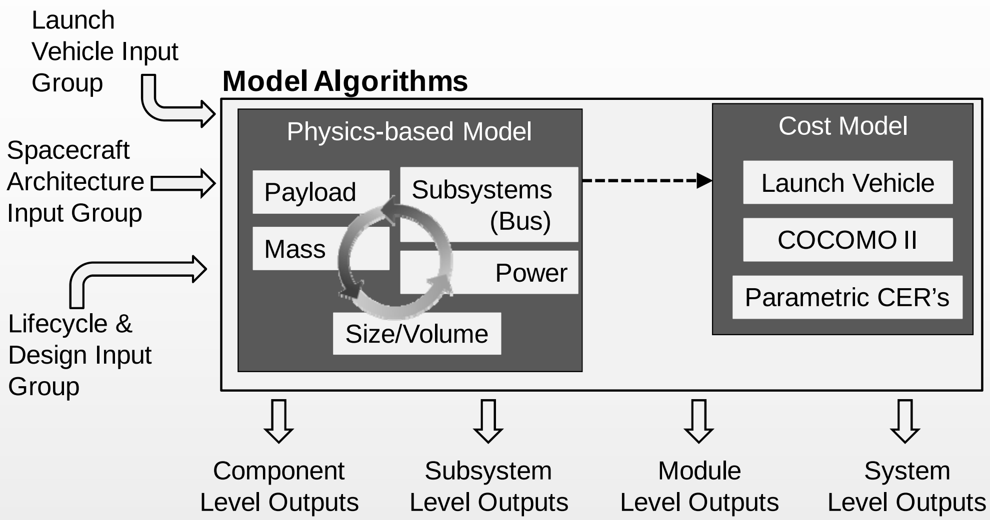
Photo: Hubble ST, http://www.nasa.gov/worldbook/hubble_telescope_worldbook.html

Deep-Space Observation Mission

	Attribute	Definition	Units	Range (least to most desirable)
1	*Mission Lifetime*	Operational duration of spacecraft	years	[5, 15]
2	*Payload Pointing Stability*	Level of pointing accuracy about dominant spacecraft inertia axis	rd	[1e-01, 1e-06]
3	*Angular Resolution*	Min. angular separation of two points that can be differentiated	mas	[1000, 1]
4	*Slew Rate*	Rate of rotation about dominant spacecraft inertia axis	rd/s	[2e-06, 1e-01]
5	*Focal Ratio*	Aperture focal length relative to its major axis diameter	-	[f/40, f/1]*

Value proposition: provide visible wavelength images of astrophysical (stellar) phenomenon, in deep space (i.e., extragalactic) for support of scientific studies for at least five years

Design Assessment Method



Model		Algorithm	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Inputs	1	SET Inputs															
Physics-Based Model	2	Mission Payload(s)	X														
	3	Computer System, C&DH	X	X													
	4	Communications, TT&C	X		X												
	5	ADS, GNS	X														
	6	EPS	X								**X**						
	7	Propulsion, ACS, GCS	X					X				**X**	**X**				
	8	TCS	X	X	X	X	X	X	X				**X**				
	9	Power Required	X	X	X	X	X	X	X	X		**X**	**X**				
	10	Mass	X	X	X	X	X	X	X	X							
	11	Size, Volume	X	X	X	X	X	X	X	X		X					
Cost Model	12	LV Selection	X	X	X	X	X	X	X	X		X	X				
	13	COCOMO II	X	X													
	14	Parametric CERs	X	X	X	X	X	X	X	X		X					
Outputs	15	SET Outputs		X	X	X	X	X	X	X	X	X	X	X	X	X	

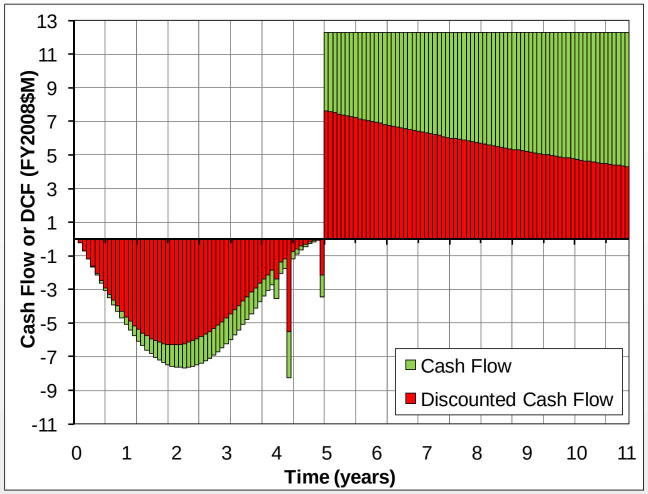
Feedback Loops

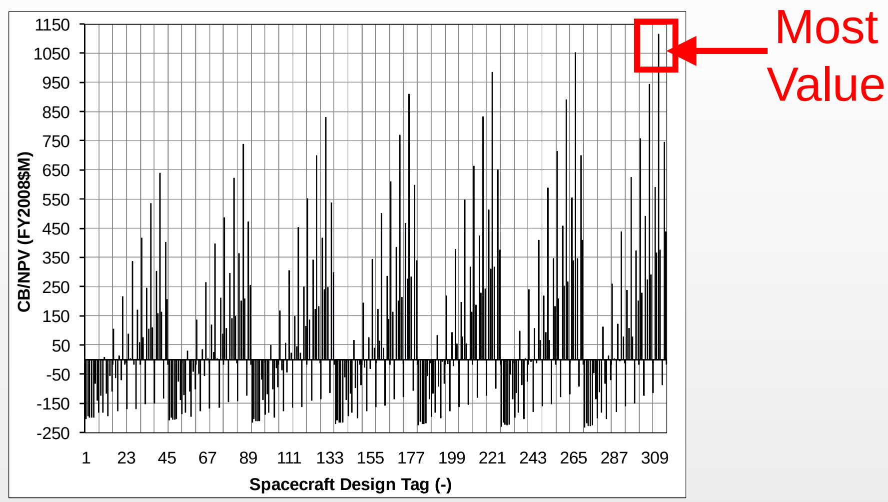
- Various spacecraft designs proposed and assessed using Spacecraft Evaluation Tool (SET)*
  - High fidelity spacecraft modeling tool developed to simulate performance of monolithic or fractionated spacecraft architectures
  - 315 designs for telecom mission; 192 for deep space mission
- Assessed metrics include
  - Lifecycle cost (both NRE and RE)
  - Attributes (both emergent and controlled)

**O'Neill, M.G., "Spacecraft Evaluation Tool Verification and Validation," MIT SEAri WP-2010-3-2 (http://seari.mit.edu), Cambridge, MA, January 2010,*

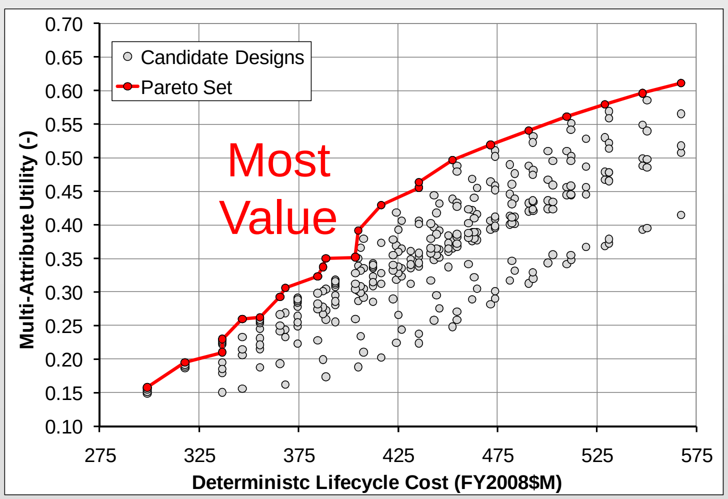
Results: Telecom

Net Present Value/Cost-Benefit Analysis





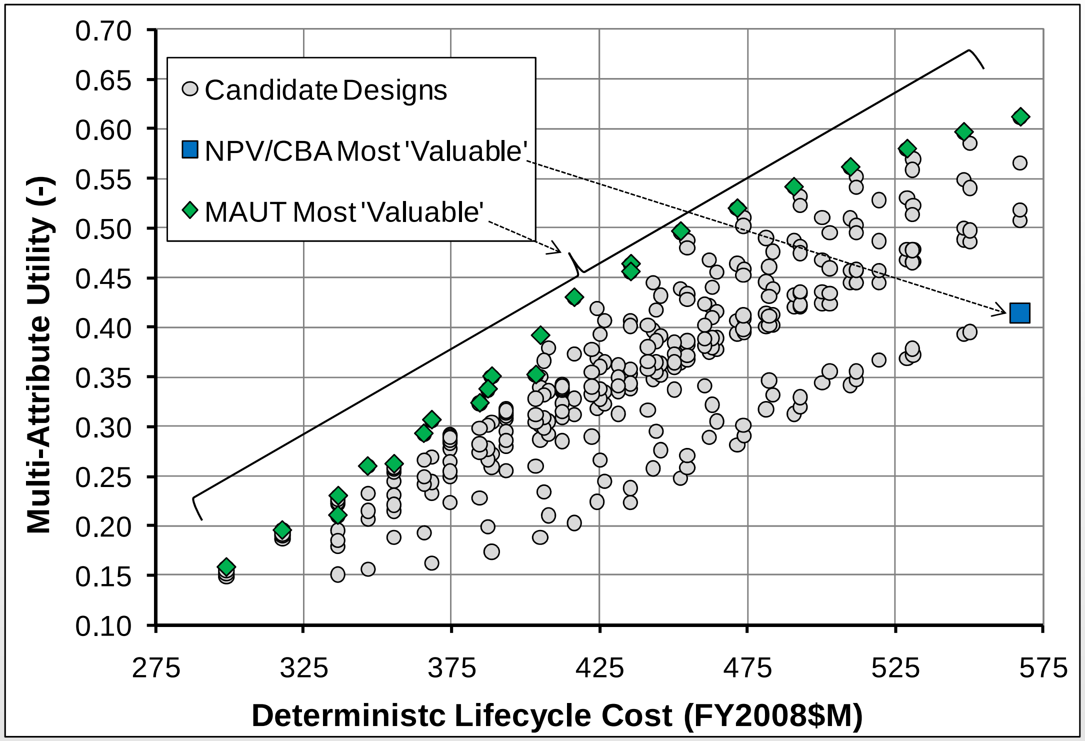
Multiple Attribute Utility Theory



Insights

- MAUT ignores revenue streams, but accounts for cost
- NPV/CBA biased to attributes responsible for most revenue
- MAUT (leads to trades) vs. NPV/CBA (selected design)
- Demonstrates the potential for competing valuation structures via differing VCDMs

Recommendation: Telecom



- MAUT
  - Supply only SD channels (max benefit per transponder)
- NPV/CBA
  - Supply only HD channels (max revenue per transponder)
- Mutually exclusive recommendations
  - Caveat: dependent on assumed stakeholder preference structure and market demand

- Considerations for Recommendations
  - Inherent assumptions in each VCDM
  - Variance in value quantification amongst and within VCDMs
    - First-order: differing cardinal/ordinal measures
    - Second-order: implicit uncertainty in “value” due to assumptions

Results & Recs: Deep Space

Net Present Value/Cost-Benefit Analysis

Net Present Value

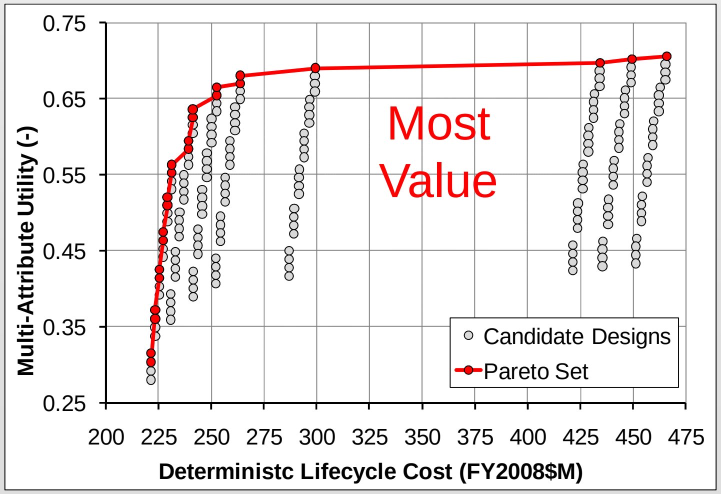
1. Quantify the initial investment for the spacecraft D_o
2. Quantify the discount rate (inflation and real) r
3. Quantify revenue (profit minus cost) generated over the course of lifecycle as a function of time $D(t)$
4. Compute the NPV via Eq. (1)

Cost-Benefit Analysis

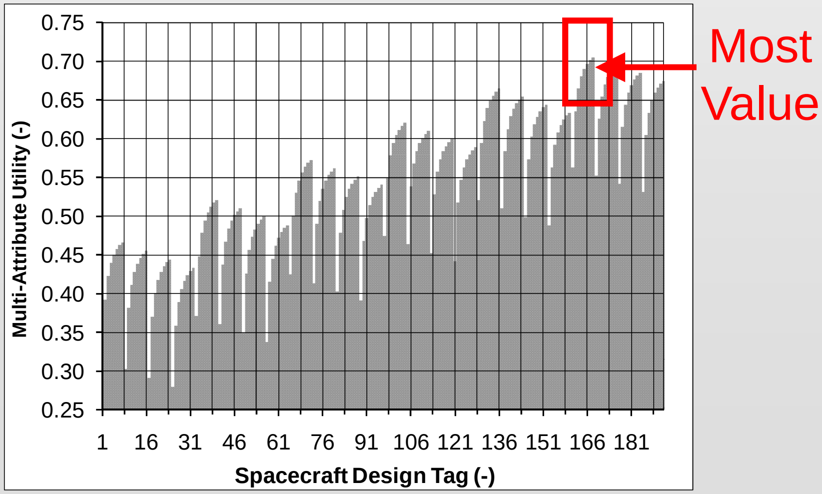
1. Quantify the discount rate (inflation and real) r
2. Quantify the cost of the spacecraft in time $C(t)$
3. Repeat for all attributes
   - Quantify monetary value of attribute$_i$ in time $v(x_i, t) = B(t)$
4. Compute the CB via Eq. (3)

- Insights
  - Literature has not demonstrated how to monetize attributes
  - MAUT is readily executable
- Recommendations
  - MAUT: long-lived system with reasonable, but not the best attribute values to keep cost down
  - NPV/CBA (no recommendation)

Multiple Attribute Utility Theory



Multiple Attribute Utility Theory (cost incl.)



Discussion

- Pick appropriate method given perspective
  - Choose meaning for “value”
  - Identify market “type”
  - Compare assumptions; weigh practicality with limitations
- Insights from case studies may be representative
  - Possible spectrum based on market “type” from commercial to military to science missions
- VDD Example: DARPA System F6 Program
  - Goal: develop and apply VCDM tools to provide risk-adjusted, net value comparison of monolithic vs. fractionated spacecraft
  - Four teams participated in Phase I, each with own VCDM
  - Each team used different valuation approach, implicit assumptions on “value” definition
  - Each came to different conclusions on the “value” of fractionated spacecraft; likely due to disparities in value perspectives and methods

Source: http://www.darpa.mil/tto/programs/systemf6/index.html

Differences in value-driven design recommendations can arise not only from technical issues (e.g., data and modeling), but also from valuation method employed

Conclusion

- No single VCDM can provide “perfect” quantification of “value”
  - Each has assumptions and limitations
  - Each may apply to different interpretations on “value” definition
  - May apply differently depending on market type
- Important to explicitly define “value” as well as reveal assumptions in method to quantify
- May be useful to leverage multiple VCDMs in order to gain insight across limiting assumptions as well as to help communicate to different communities
- It is essential to be consistent in application and communication of methods in order to properly compare results across studies and increase confidence in results

Balancing practicality, rigor, and appropriateness, aligning perspectives and methods should be an explicit activity for value-driven design