Quantifying Flexibility in the Operationally Responsive Space Paradigm

Lauren Viscito and Adam M. Ross

September 15, 2009

Track 50-SSEE-5: Value Driven Design
AIAA Space 2009

The views expressed in this article are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.

Agenda

- Introduction
- Tradespace Networks
- Value Weighted Filtered Outdegree
- Responsive System Comparison
- SRS Case Application
- Conclusions

© 2009 Massachusetts Institute of Technology

Uncertainty in System Design

- Engineers build complex systems in presence of uncertainty
  - lack of knowledge
  - lack of definition
- Uncertainty can lead to risk
- Also presents opportunity
- Two uncertainties considered:
  - stakeholder preference changes
  - environmental changes

Performance risk	Uncertainty in the ability of a design to meet desired quality criteria (along any one or more dimensions of merit, including price and timing) and the consequences thereof
Schedule risk	Uncertainty in the ability of a project to develop an acceptable design (i.e., to sufficiently reduce performance risk) within a span of time and the consequences thereof
Development cost risk	Uncertainty in the ability of a project to develop an acceptable design (i.e., to sufficiently reduce performance risk) within a given budget and the consequences thereof
Technology risk	A subset of performance risk: uncertainty in capability of technology to provide performance benefits (within cost and/or schedule expectations) and the consequences thereof
Market risk	Uncertainty in the anticipated utility or value to the market of the chosen "design to" specifications (including price and timing) and the consequences thereof
Business risk	Uncertainty in political, economic, labor, societal, or other factors in the business environment and the consequences thereof

Table 1: Definitions of Dimensions of Product Development Risk

(Browning, 1998)

In the presence of uncertain future use of the system, designers want to build in risk mitigation, but should also consider ways to take advantage of emergent opportunities

(Thunnisen, 2004, McManus, 2005, Browning, 1998, Fricke, 2005)

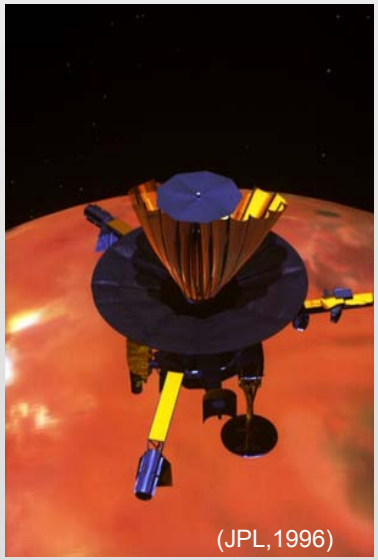
© 2009 Massachusetts Institute of Technology

Flexible Systems

- Global Positioning System
  - Designed for military navigation and timing
  - Included civilian channel
  - Unanticipated commercial industry built around GPS signal

(Boeing, 2009)

Uncertainty in market → system able to "change" to take advantage of opportunity


(JPL,1996)

- Galileo (Jupiter probe)
  - High gain antenna failed to deploy
  - Mission did not fully recover from anomaly
  - Could have used motor with reverse to 'rock' ribs, but sacrificed component in design phase

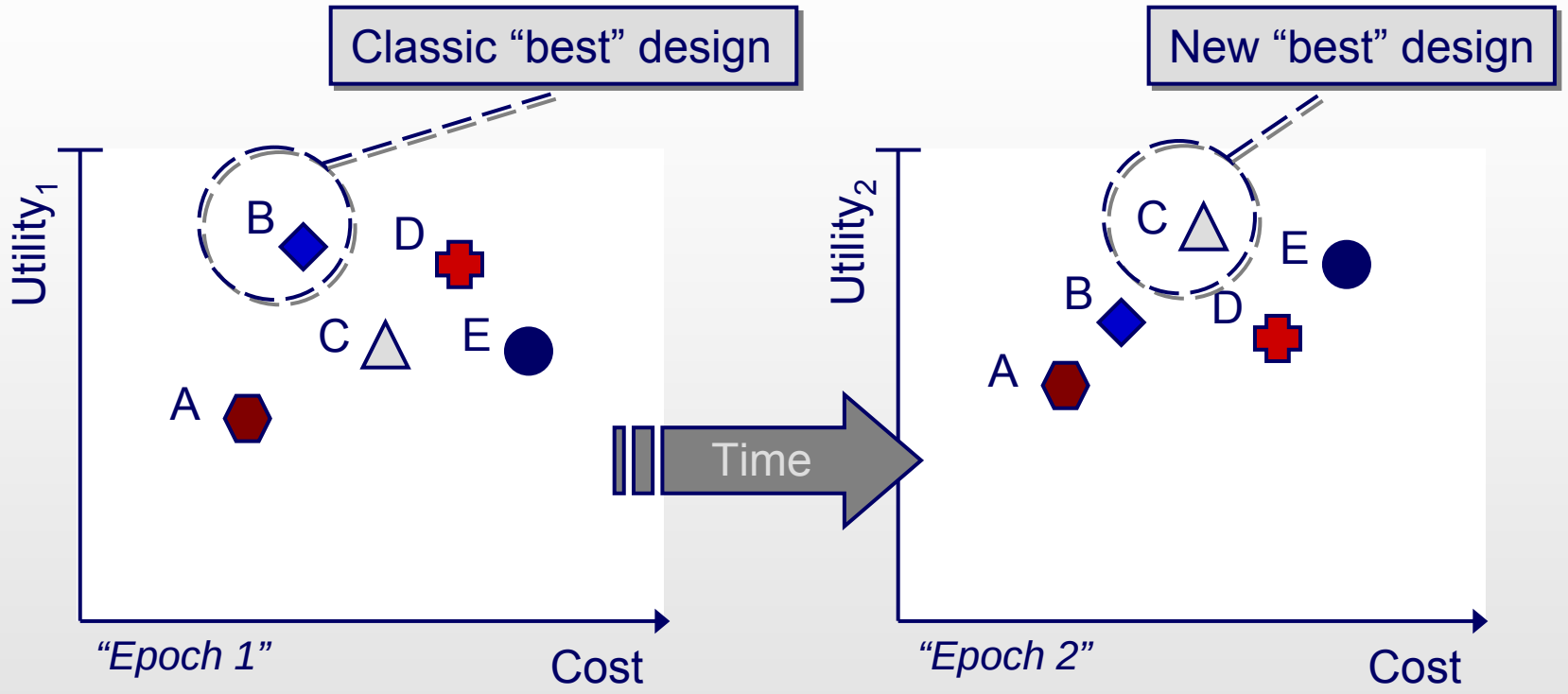
(McManus, 2004)

Uncertainty in environment → system unable to physically change to mitigate risk*

*ability to "change" software did allow for partial mission recovery

© 2009 Massachusetts Institute of Technology

Tradespace Exploration: Finding "Best" Designs

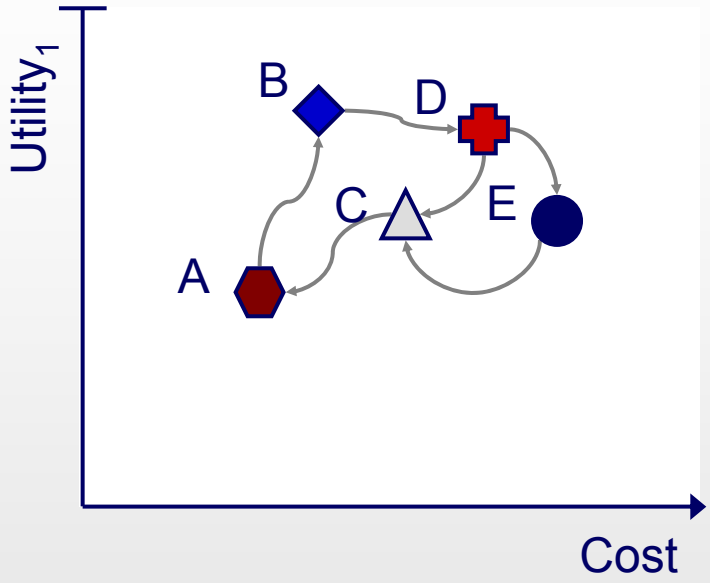


Changes in expectations and environment can affect the apparent value of a design over time

If the "best" design changes over time, how can one find the "best" design?

© 2009 Massachusetts Institute of Technology

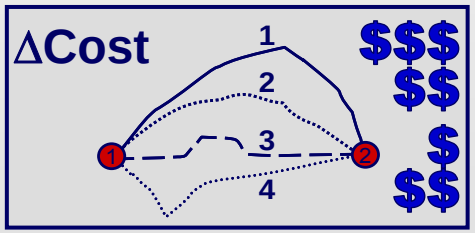
Generate Tradespace Networks

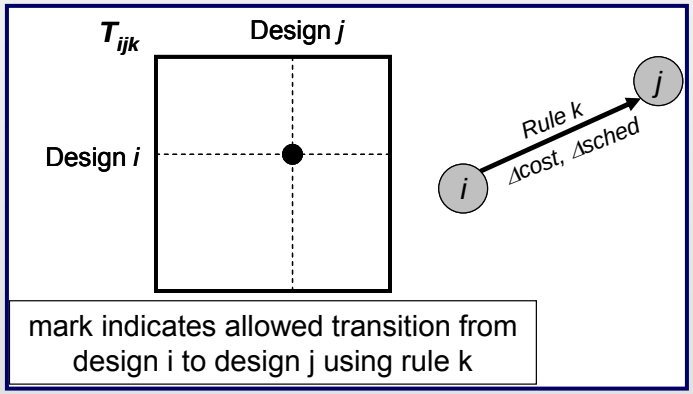


Tradespace networks

Tradespace designs = nodes

Applied transition rules = arcs

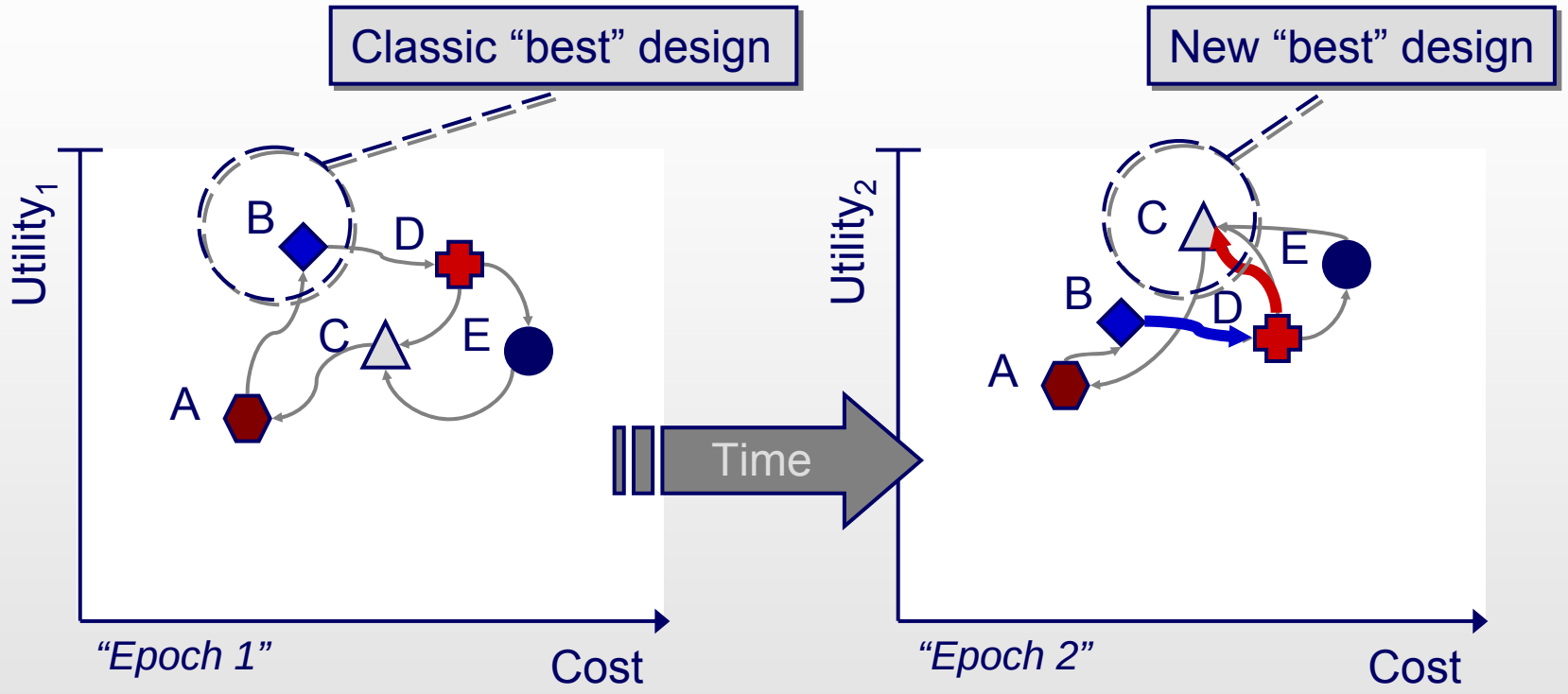




- Specify transition mechanisms/rules for system state change within tradespace
- Many rules possible (e.g. “add spare satellite”, “burn on board fuel to change apogee,” etc.)

© 2009 Massachusetts Institute of Technology

Tradespace Networks: Changing Designs over Time



“Best” designs in new contexts may differ; Flexibility may provide opportunity

© 2009 Massachusetts Institute of Technology

Valuable Flexibility

Valuable Flexibility is a dynamic property of a system that allows it to take advantage of emergent opportunity and to mitigate risk, by enabling the system to respond to changing contexts, in order to retain or increase usefulness to system stakeholders over time.

- Tradespace exploration results in a large number of potential designs
- Operationalizing flexibility for tradespace exploration will aid decision makers during conceptual design to find potentially "interesting" designs
- Practical and useful way to measure valuable flexibility lacking in TSE
  - Measuring flexibility is often domain specific or descriptive in nature
  - Assigning a dollar value is not suitable for explicitly trading designs

Identifying valuably flexible designs is essential for trading flexibility.
Need a metric tailored for tradespace exploration design methods.

(Childs, 1998, De Neufville, 2002, Cardin, 2007, Ibanez, 2004, Kalligeros, 2006, Olewnik, 2007, Shuiabu, 2004, Ross 2008a)

© 2009 Massachusetts Institute of Technology

Value Weighted Filtered Outdegree (VWFO)

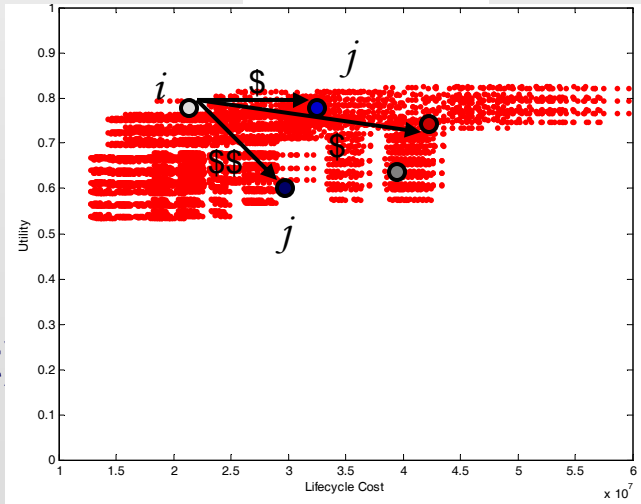
Valuably flexible designs are changeable designs whose transitions increase utility over changing contexts

- Identifies higher value designs, like Pareto Tracing
- Uses Filtered Outdegree to determine changeability $Arc_{i,j} = \sum_k T_{i,j,k}$
- Considers designs over change in context

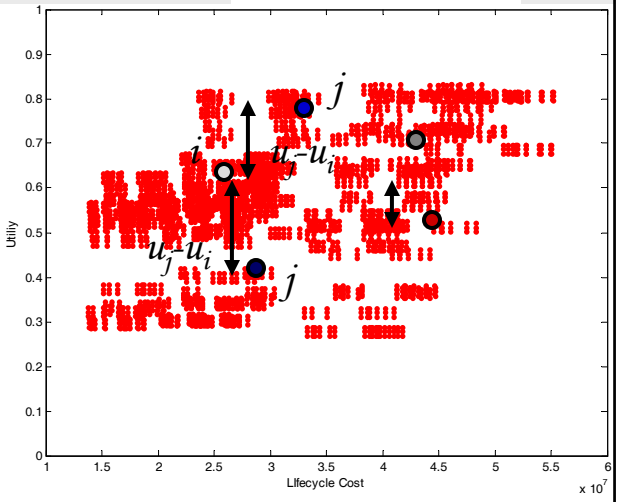
$$VWFO_i^{m,m+1} = \frac{1}{N-1}\sum_{j=1}^{N-1}[sgn(u_j^{m+1} - u_i^{m+1}) * Arc_{i,j}^{m}]$$

N = number of designs
i = origin design
j = destination design
Arc = transition allowed
m = current time (context)
m+1 = future time (context)
u = utility of design

Epoch A (m)



Epoch B (m+1)



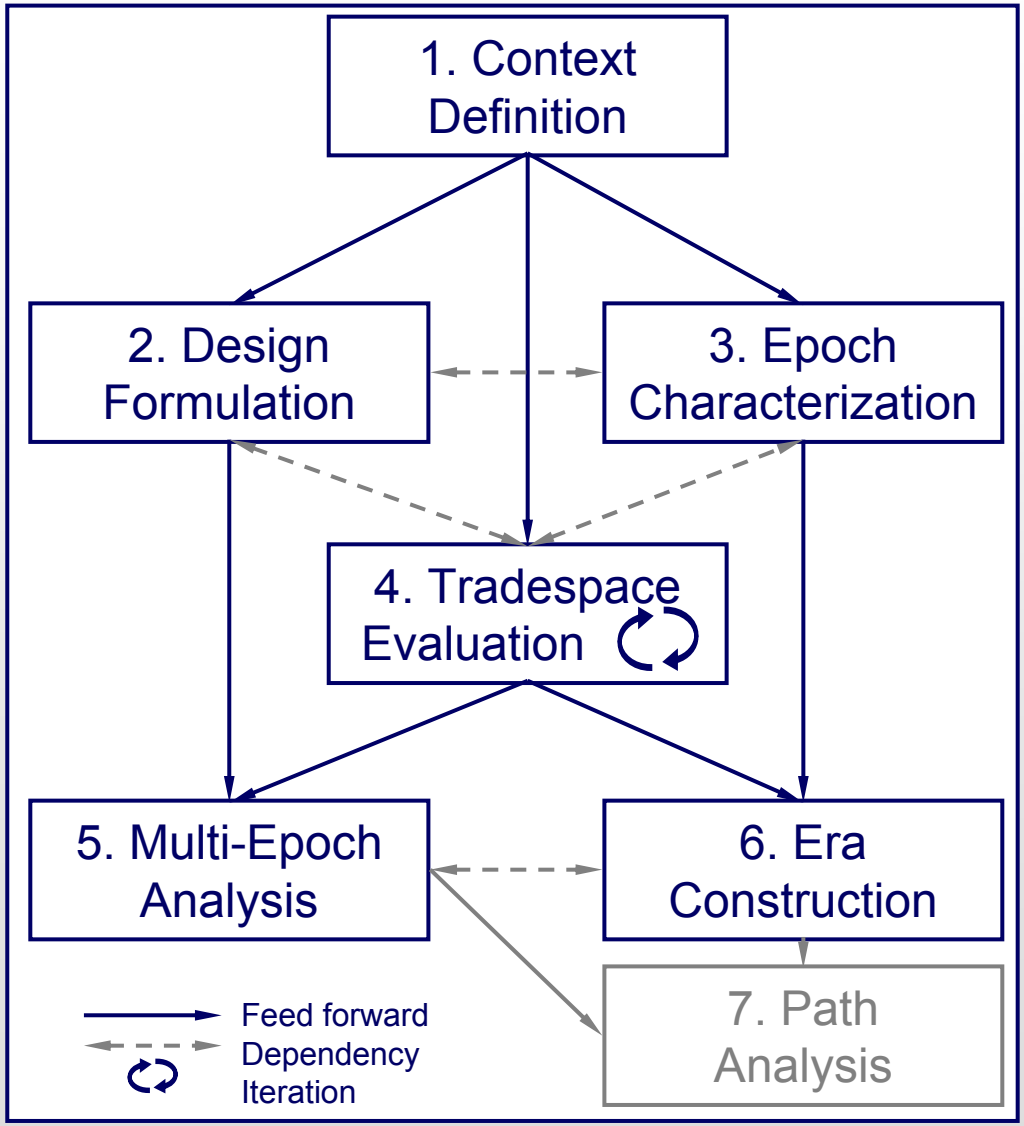
© 2009 Massachusetts Institute of Technology

Responsive System Comparison

- Framework for implementation of Dynamic MATE and Epoch-Era Analysis
- Seven processes conducted in iterative manner
- Explicitly incorporates time-dependent context changes

RSC used to generate tradespace data for case study

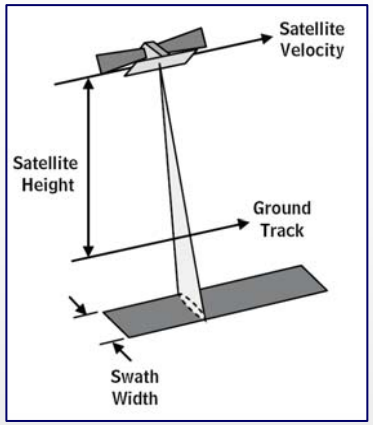
(Ross 2003, Ross 2006, Ross 2008a, Roberts 2009)



© 2009 Massachusetts Institute of Technology

Satellite Radar System Case Application

- Leverage large ongoing study
- Rich tradespace with many path enablers (e.g. “spare satellites,” “extra fuel”)
- Extensive look at epochs (changing contexts)
  - Stakeholder preferences
  - Technology changes
  - Mission application scenarios
- Analysis did not identify a ‘best’ changeable design



(CBO 2007)

Unit-of-analysis: SR architecture
- Radar payload
- Constellation of satellites
- Communications network

Satellite Radar System (SRS) Value Proposition:

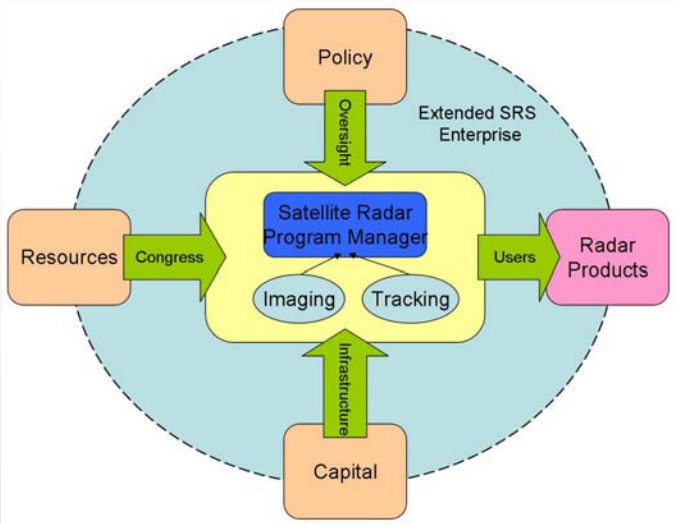
24 hour, all weather on-demand “Visibility and Tracking” over things that can be observed

(Ross, 2008b)

© 2009 Massachusetts Institute of Technology

1. Context Definition

- Program Manager acts as high-level decision maker for trading
  - Imaging stakeholder
  - Tracking stakeholder
- External stakeholders
  - Congress
  - Oversight agencies
  - Product users



© 2009 Massachusetts Institute of Technology

2. Design Formulation

TABLE 4-1: Attributes for Satellite Radar System

Attribute	Description
Imaging Mission	
Imaging Latency	The time between the imaging of a given target and when the full target image is downloaded to the ground
Field of View	The area of the earth that the Radar has access to within its normal range of motion
Geolocation Accuracy	The system's reported location of an image on the surface
Number of Targets Per Pass	The number of targets the Radar can image within a given target box for a single pass
Revisit Gap Time	The number of observations (i.e., passes) of a given target over the course of a single day
Resolution	The minimum separation between two targets that permits them to be distinguished by the Radar
Tracking Mission	
Tracking Latency	The time between the imaging of a given target and when the full target image is downloaded to the ground
Track Life	Length of time that a single target can be tracked (continually imaged)
Target Acquisition Time	The time interval between receiving a tasking order to observe a given location and actually acquiring the target as a function of gap time and target detection time
Min Detectable Velocity	Minimal velocity at which a target can be distinguished from the background
Number of Target Boxes	The number of target boxes (defined at a given size (Km2) and consisting of targets with a given velocity and Radar Cross Section) that can be imaged by a single satellite during a single pass
Min Radar Cross Section	The minimal signal reflected from a target in response to a pulse that is capable of being detected by the radar's receiver

Elicited value metrics

- Attribute sets for each mission area
  - informal interview process
  - Utility curves estimated by team

TABLE 4-2: Satellite Radar System Attribute Weights

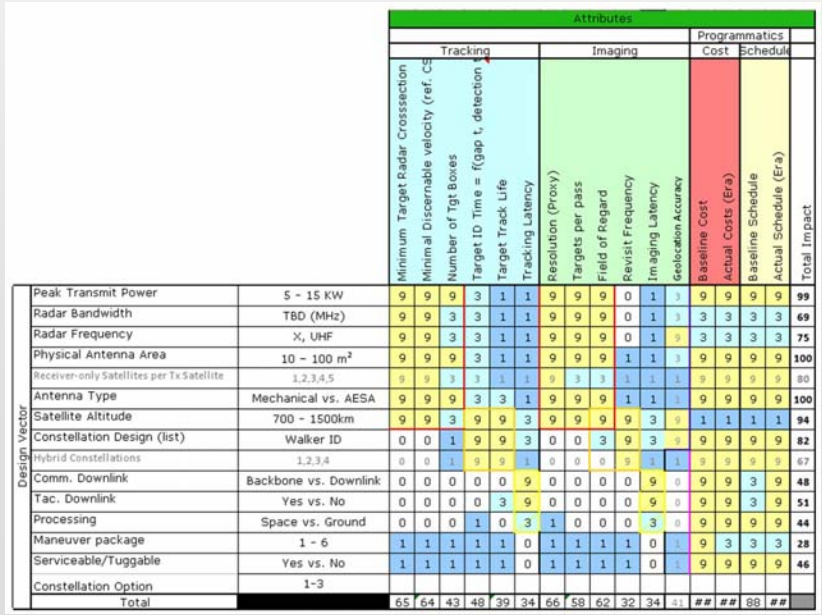
Attribute	Weight
Imaging Mission	
Imaging Latency	0.04
Field of View	0.13
Self Geolocation	0.04
Number of Targets Per Pass	0.38
Revisit Gap Time	0.04
Resolution	0.38
Tracking Mission	
Tracking Latency	0.38
Track Life	0.13
Target Acquisition Time	0.04
Min Detectable Velocity	0.04
Number of Target Boxes	0.38
Min Radar Cross Section	0.04

© 2009 Massachusetts Institute of Technology

2. Design Formulation (2)

Proposed design parameters

- Design Variables specify the system concept and must drive value in both mission areas



		Attributes																
		Tracking						Imaging						Programmatics				
		Minimum Target Radar Crosssection	Minimal Discernable velocity (ref. CS	Number of Tgt Boxes	Target ID Time = f(gap t, detection	Target Track Life	Tracking Latency	Resolution (Proxy)	Targets per pass	Field of Regard	Revisit Frequency	Imaging Latency	Geolocation Accuracy	Baseline Cost	Actual Costs (Era)	Baseline Schedule	Actual Schedule (Era)	Total Impact
Design Vector	Peak Transmit Power	5 - 15 KW	9	9	9	3	1	1	9	9	9	0	1	3	9	9	9	9	99
	Radar Bandwidth	TBD (MHz)	9	9	3	3	1	1	9	9	9	0	1	3	3	3	3	3	69
	Radar Frequency	X, UHF	9	9	3	3	1	1	9	9	9	0	1	9	3	3	3	3	75
	Physical Antenna Area	10 - 100 m^2	9	9	9	3	1	1	9	9	9	1	1	3	9	9	9	9	100
	Receiver-only Satellites per Tx Satellite	1,2,3,4,5	9	9	3	3	1	1	9	3	3	1	1	1	9	9	9	9	80
	Antenna Type	Mechanical vs. AESA	9	9	9	3	3	1	9	9	9	1	1	1	9	9	9	9	100
	Satellite Altitude	700 - 1500km	9	9	3	9	9	3	9	9	9	9	3	9	1	1	1	1	94
	Constellation Design (list)	Walker ID	0	0	1	9	9	3	0	0	3	9	3	9	9	9	9	9	82
	Hybrid Constellations	1,2,3,4	0	0	1	9	9	1	0	0	0	9	1	1	9	9	9	9	67
	Comm. Downlink	Backbone vs. Downlink	0	0	0	0	0	9	0	0	0	0	9	0	9	9	3	9	48
	Tac. Downlink	Yes vs. No	0	0	0	0	3	9	0	0	0	0	9	0	9	9	3	9	51
	Processing	Space vs. Ground	0	0	0	1	0	3	1	0	0	0	3	0	9	9	9	9	44
	Maneuver package	1 - 6	1	1	1	1	1	0	1	1	1	1	0	1	9	3	3	3	28
	Serviceable/Tuggable	Yes vs. No	1	1	1	1	1	0	1	1	1	1	0	1	9	9	9	9	46
	Constellation Option	1-3																	
	Total		65	64	43	48	39	34	66	58	62	32	34	41	##	##	88	##	

TABLE 4-3: Design Variables for Satellite Radar System Case Application

Design Variable	Description
Peak Transmit Power (1.5 10 20 [kW])	The amount of power that is used to send the radar signal to illuminate the target area. The higher the power sent, the higher the return signal, in general
Radar Bandwidth (0.5 1 2 [GHx])	The bandwidth of the radar signal. Larger bandwidths generally return better signatures, but have less power spectrum and so require more power
Antenna Area (10 40 100 [m^2])	The size of the AESA array.
Altitude (800 1200 1500 [km])	The altitude of the satellite in orbit
Constellation Design (8 Walker IDs[a])	The Walker configuration that is chosen for the spacecraft
Comm Downlink (Relay or Downlink)	Whether the satellite has a communications system able to use a dedicated communications backbone, such as TDRSS
Tactical Downlink (Yes or No)	Whether the satellite is designed with a high power, localized downlink for tactical users
Maneuver Package (1x, 2x, 4x)	The total amount of maneuvering fuel on-board the satellite
Constellation Option (none, long-lead, spare)	What real option is built into the supply chain

[a] Walker ID is a lookup table of characteristics for a Walker constellation, with different possibilities for number of satellites and the phase(plane orientation).

23,328 design permutations

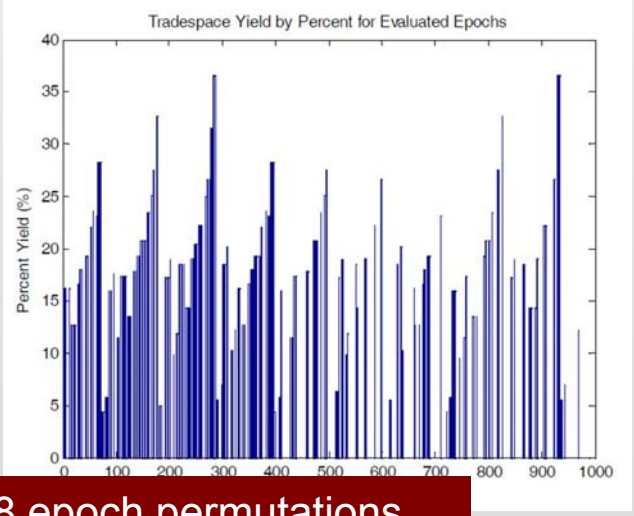
© 2009 Massachusetts Institute of Technology

3. Epoch Characterization

- Epoch uncertainty categories identified
- Variables chosen based on likelihood of change
- Tradespace Yield illustrates effect of epoch variables on design space

TABLE 4-4: Epoch Variables for Satellite Radar System Case Application

Epoch Variable	Levels	Description
National Security Policy	Notional Target Sets	9 scenarios
	User Priority (Image vs Track)	SAR = GMTI, SAR< GMTI, SAR > GMTI
Technology	Available Technology Levels	High, Med, Low
Infrastructure	Communications Infrastructure	2 Levels
Systems-of-Systems	Airborne ISR Assets	2 Levels
Environment	Communications Jamming	none, 10dB

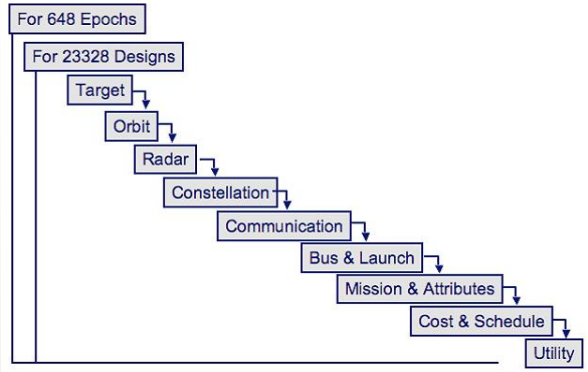


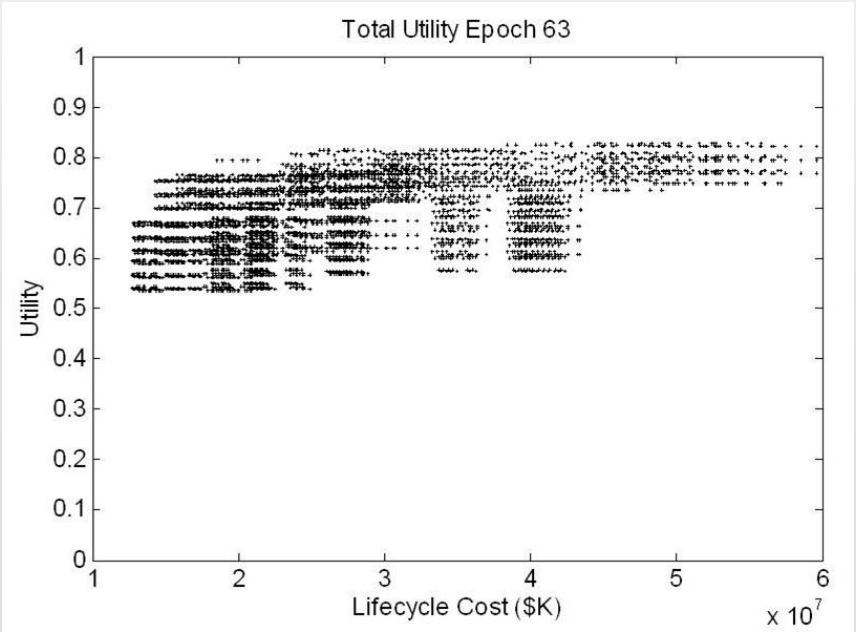
648 epoch permutations

© 2009 Massachusetts Institute of Technology

4. Tradespace Evaluation

- Extensive modeling and validation effort
  - 23,328 Designs
  - 648 Epochs (245 simulated)
- Design variable impact on attributes





Total Utility, an epoch level linear combination of the mission utilities is displayed in all tradespace plots.

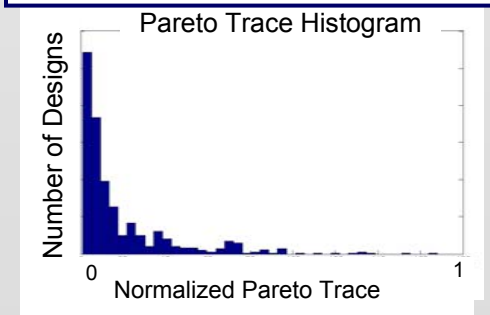
© 2009 Massachusetts Institute of Technology

5. Multi-Epoch Analysis

- Designs with high **Pareto Trace** are 'passively value robust'
  - Retain high utility over many epochs- deliver high value
  - Tend to be close to constraint boundaries
- These designs are often considered the 'best' across tradespace
  - Not changeable designs
  - Extreme context changes negate robustness

TABLE 4-5: Utility for High Normalized Pareto Trace Designs

Design Number	Normalized Pareto Trace	Total Utility Epoch 63	Epoch 171	Epoch 193	Epoch 202
3435	0.69	0.75	0.75	0.57	0.66
3447	0.55	0.76	0.76	0.63	0.73
3555	0.56	0.82	0.82	0.81	0.90
6027	0.62	0.76	0.76	0.55	0.65
6039	0.53	0.76	0.76	0.61	0.71
6147	0.53	0.81	0.81	0.81	0.90



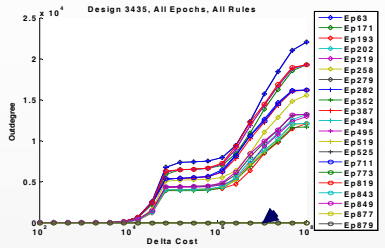


TABLE 4-5: Utility for High Normalized Pareto Trace Designs

Design Number	Normalized Pareto Trace	Total Utility Epoch 63	Epoch 171	Epoch 193	Epoch 202
3435	0.69	0.75	0.75	0.57	0.66
3447	0.55	0.76	0.76	0.63	0.73
3555	0.56	0.82	0.82	0.81	0.90
6027	0.62	0.76	0.76	0.55	0.65
6039	0.53	0.76	0.76	0.61	0.71
6147	0.53	0.81	0.81	0.81	0.90

- High **Filtered Outdegree** designs are highly changeable
  - Able to *transition* to other designs in the tradespace
  - Including change mechanisms drive designs away from Pareto Optimal – pay for changeability
- In presence of uncertainty, changeability instead of robustness may be desirable
  - Does not imply value of changes
  - Calculated in a static context

(Ross 2006, Ross, 2009)

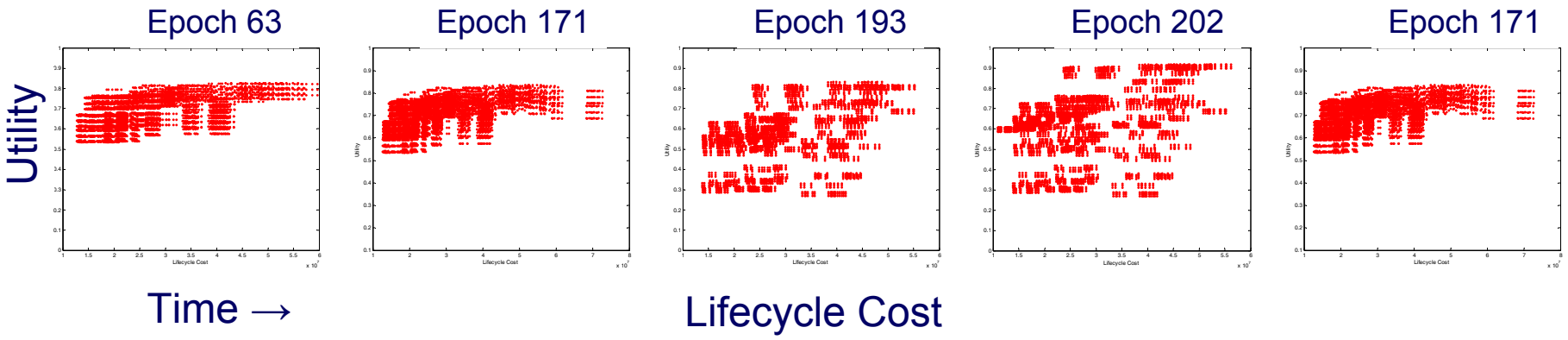
© 2009 Massachusetts Institute of Technology

6. Era Construction

- Era selected for detailed study
- Highlights stakeholder preference change

TABLE 4-7: Description of Epochs in Era 1

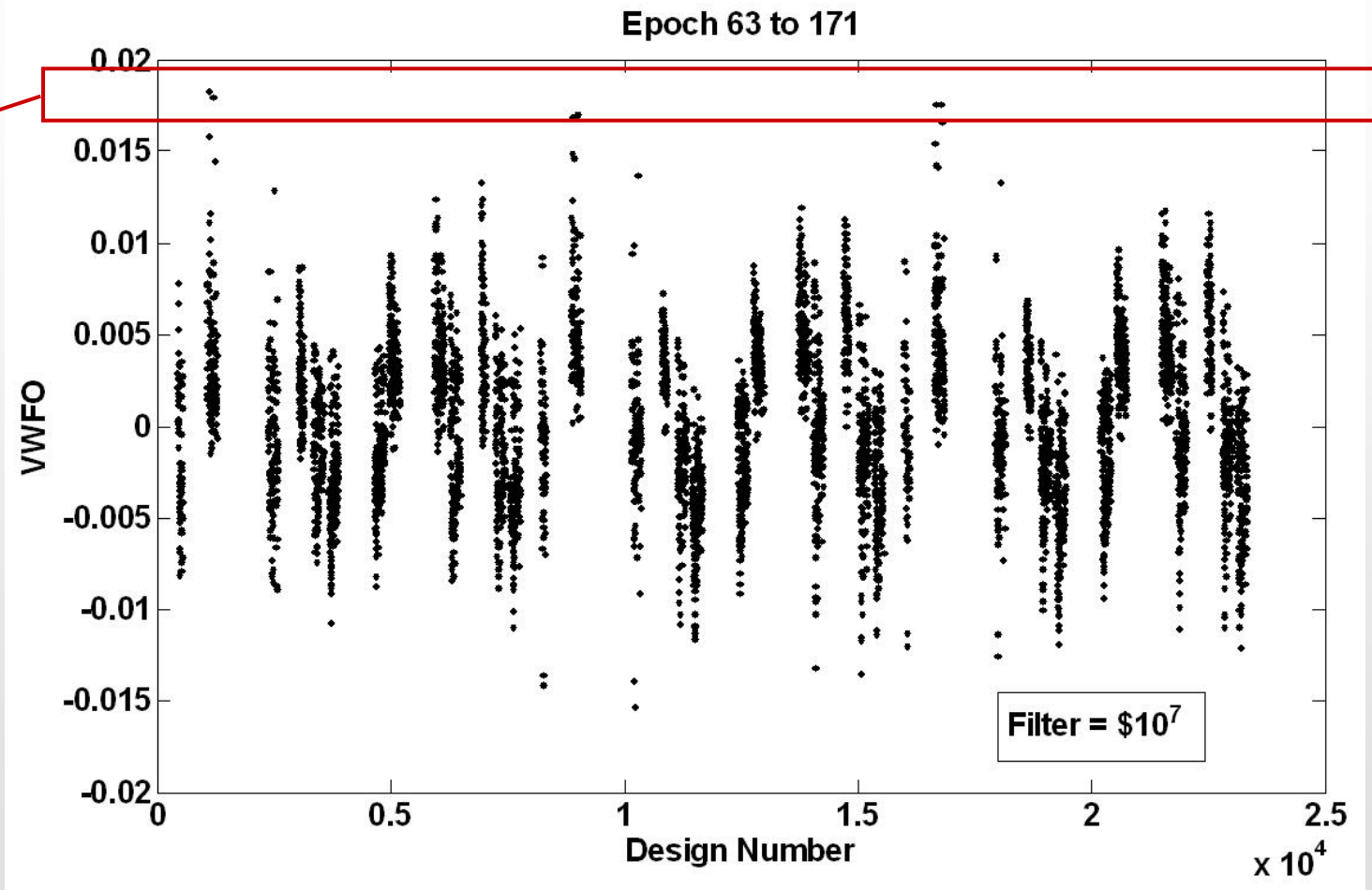
Epoch Number	Duration (yrs)	Description	Epoch Vector
63	2	Today	Scenario 60, SAR > GMTI, Low tech level, No backbone, No AISR, No jamming
171	4	Natural advancement in Comm capability	Scenario 60, SAR > GMTI, Low tech level, Backbone, No AISR, No jamming
193	1	New threat- Mobile missile launchers	Scenario 94, SAR > GMTI, Low tech level, Backbone, No AISR, No jamming
202	3	Increased Conflict, UAVs deployed, Jamming	Scenario 94, SAR < GMTI, Low tech level, Backbone, AISR, Jamming
171	3	Conflict Resolved, back to pre-conflict state	Scenario 60, SAR > GMTI, Low tech level, Backbone, No AISR, No jamming



© 2009 Massachusetts Institute of Technology
(Roberts, 2009)

Value Weighted Filtered Outdegree by Design Number

Valuably flexible designs?



VWFO can be used to quickly screen tradespace for changeable designs that result in net positive utility gains across epoch change in era

© 2009 Massachusetts Institute of Technology

VWFO for Selected Designs

Systems Engineering Advancement Research Initiative

Designs selected by FOD or PT

TABLE 4-8: Value Weighted Filtered Outdegree for Selected Designs with high Filtered Outdegree or high Pareto Trace

Design Number	Value Weighted Filtered Outdegree			
	63 to 171	171 to 193	193 to 202	202 to 171
1089	0.0044	0.0048	0.0000	0.0000
1101	0.0085	0.0097	0.0021	0.0032
3435	-0.0057	-0.0021	-0.0034	-0.0031
3447	-0.0035	-0.0017	-0.0031	-0.0027
3555	-0.0014	-0.0006	-0.0014	-0.0014
6027	0.0044	0.0054	0.0020	0.0024
6039	0.0027	0.0031	0.0023	0.0027
6147	0.0019	0.0022	0.0014	0.0017
8921	0.0147	0.0187	0.0064	0.0072
9029	0.0000	0.0388	0.0077	0.0091
16701	0.0089	0.0138	0.0043	0.0051
16809	0.0000	0.0138	0.0059	0.0067

Designs selected by VWFO

TABLE 4-9: Design with High Value Weighted Filtered Outdegree

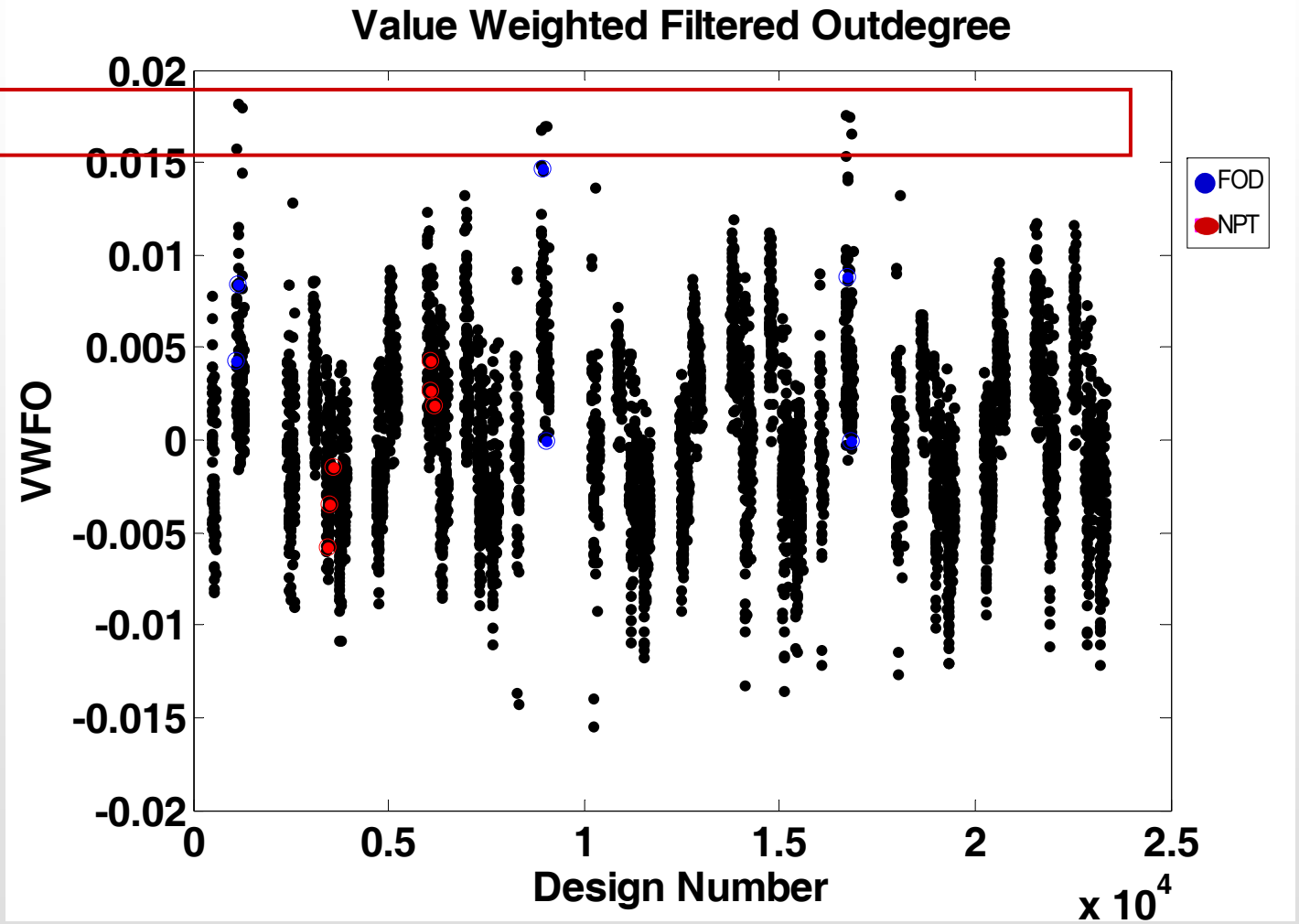
Design Number	Value Weighted Filtered Outdegree			
	63 to 171	171 to 193	193 to 202	202 to 171
1097	0.0159	0.0166	0.0054	0.0054
1109	0.0183	0.0228	0.0079	0.0080
1205	0.0180	0.0213	0.0077	0.0074
8873	0.0149	0.0125	0.0038	0.0049
8885	0.0168	0.0165	0.0053	0.0072
8921	0.0147	0.0187	0.0064	0.0072
8981	0.0171	0.0177	0.0056	0.0068
9017	0.0171	0.0193	0.0066	0.0072
16649	0.0154	0.0138	0.0044	0.0052
16661	0.0176	0.0188	0.0063	0.0076
16757	0.0176	0.0192	0.0064	0.0071
16793	0.0166	0.0208	0.0074	0.0070

- Different designs selected by VWFO than other TSE metrics
- Screening metrics help to reduce large tradespaces for focused analysis and decision making

© 2009 Massachusetts Institute of Technology

Finding "Interesting" Designs

Valuably flexible designs

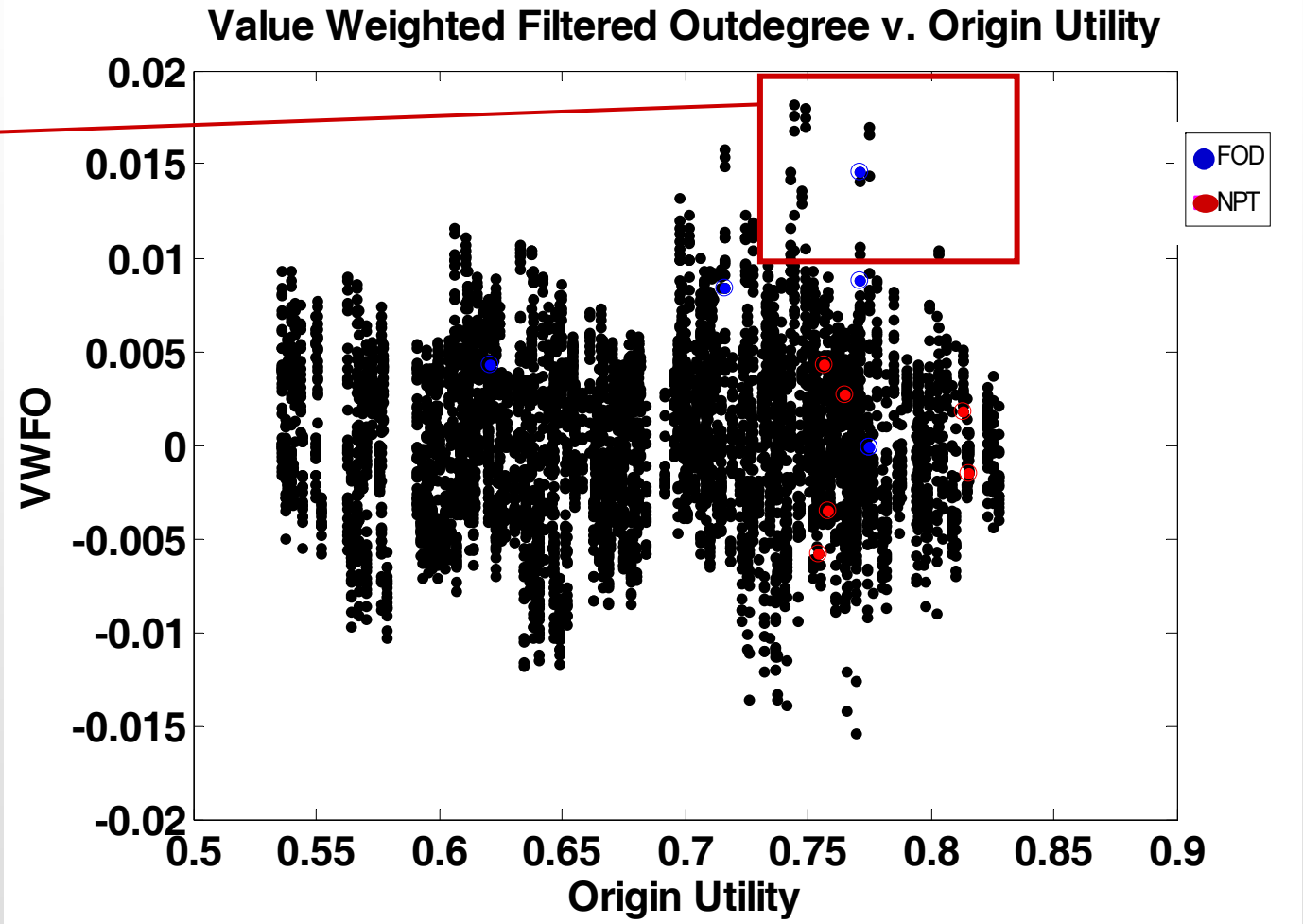


VWFO finds different interesting designs than previous tradespace metrics

© 2009 Massachusetts Institute of Technology

Valuably Flexible vs. Utility

Both high utility and valuably flexible

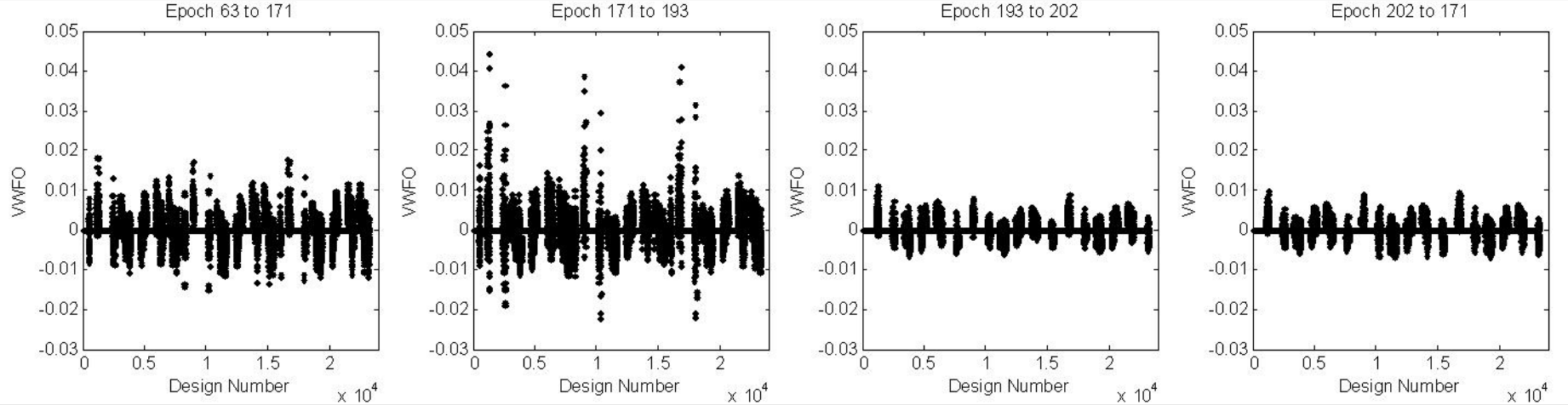


Designs can be valuably flexible (across epochs) and valuable (within epoch)

© 2009 Massachusetts Institute of Technology

VWFO for Era 1

VWFO calculation can be repeated pair-wise across an era



- Across epoch transitions, high VWFO designs can be selected for strategies across a given era
- Designs that appear high VWFO across an era may indicate more general valuable flexibility
- Across many eras, high VWFO designs can be quickly identified for further investigation into their design features

© 2009 Massachusetts Institute of Technology

Related Designs

- 'Related' designs show the effect of adding path enablers to SRS designs, with baseline design (lowest number) having lowest estimated cost
- Robust design family (high PT) has negative VWFO, all close to zero
- Changeable design family has higher VWFO than robust, but increased cost estimates
- VWFO family has designs with high VWFO and low cost increases

Path enablers

Design Number	VWFO	Maneuver Level	Constellation Option	Lifecycle Cost ($M)	Diff from Baseline ($M)	Percent Diff
Pareto Trace						
3435	**-0.0057**	**4**	**1**	**14.29**		
3439	-0.0040	5	1	14.66	0.38	0.03
3443	0.0020	6	1	15.58	1.29	0.09
11211	-0.0027	4	2	17.11	2.82	0.20
11215	-0.0016	5	2	17.57	3.28	0.23
11219	-0.0007	6	2	18.65	4.36	0.31
18987	-0.0032	4	3	17.48	3.19	0.22
18991	-0.0020	5	3	17.99	3.70	0.26
18995	-0.0001	6	3	19.17	4.88	0.34
Filtered Outdegree						
1141	0.0021	4	1	13.27		
1145	0.0102	5	1	13.65	0.38	0.03
1149	0.0027	6	1	14.41	1.14	0.09
8917	0.0081	4	2	17.96	4.69	0.35
8921	**0.0147**	**5**	**2**	**18.51**	**5.25**	**0.40**
8925	0.0107	6	2	19.60	6.33	0.48
16693	0.0060	4	3	18.55	5.29	0.40
16697	0.0141	5	3	19.20	5.94	0.45
16701	0.0089	6	3	20.49	7.22	0.54
Value Weighted Filtered Outdegree						
1105	0.0058	4	1	31.19		
1109	**0.0183**	**5**	**1**	**31.84**	**0.65**	**0.02**
1113	0.0085	6	1	33.14	1.95	0.06
8881	0.0089	4	2	35.61	4.42	0.14
8885	0.0168	5	2	36.34	5.15	0.17
8889	0.0123	6	2	37.79	6.60	0.21
16657	0.0073	4	3	36.18	4.99	0.16
16661	0.0176	5	3	36.95	5.76	0.18
16665	0.0104	6	3	38.49	7.30	0.23

Addition of path enablers may correlate to high VWFO and suggest worthwhile investment for increasing valuable flexibility

© 2009 Massachusetts Institute of Technology

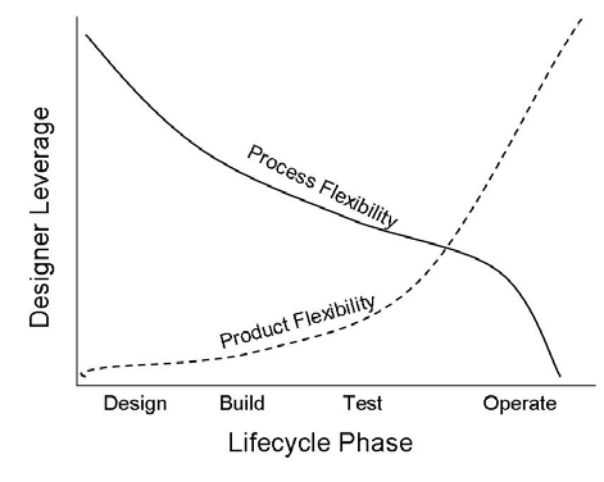
Discussion

- Limitations of metric
  - Only rough quantification of value
  - Only valid pair-wise across epochs
  - Counts both positive and negative utility differences
- Future work
  - Develop aggregate VWFO for era
  - Develop aggregate across many pair-wise epochs
  - Apply to more case studies
  - Examine effect of VWFO functions on decision making
  - Positive transition only form
  - Application to path planning

© 2009 Massachusetts Institute of Technology

Highlights from Research

- Value from flexibility is context change dependent
- Enumeration of uncertainties (risks) is essential for identifying valuably flexible designs
- Depending on phase in lifecycle when context change occurs, leverage different flexibility types



© 2009 Massachusetts Institute of Technology

Thank you for your attention!

Questions?

lauren.viscito@alum.mit.edu

SEA RI
Systems Engineering Advancement Research Initiative

Backups

References (1)

A. N. Ajah, P. M. Herder, J. Grievink, and M. P. C. Weijnen. Framework for proper integration of flexibility in conceptual designs of energy and industrial infrastructures. In L. Puigjaner and A. Espuna, editors, European Symposium on Computer Aided Process Engineering, 2005.

D. A. Bearden. A complexity-based risk assessment of low-cost planetary mission: when is a mission too fast and too cheap? Acta Astronautica, (52):8, 2002.

R. E. Bitten, D. A. Bearden, N. Y. Lao, and T. H. Park. The effect of schedule constraints on the success of planetary missions. Acta Astronautica, (59):8, 2005.

Boeing. Global Positioning System. Technical report, Boeing, http://www.boeing.com/defense-space/space/gps/index.html, 2009. Picture.

J. Browne, D. Dubois, K. Rathmill, S. P. Sethi, and K. E. Stecke. Classification of flexible manufacturing systems. The FMS Magazine, 2(2):114–117, 1984.

T. R. Browning. Modeling and Analyzing Cost, Schedule, and Performance in Complex System Product Development. PhD thesis, Massachusetts Institute of Technology, 1998.

T. R. Browning and R. V. Ramasesh. A survey of activity network-based process models for managing product development projects. Production and Operations Management, 16(2):24, 2007.

L. J. Cantafio. Space-based Radar Handbook. Artech House, Boston, MA, 1989. M.-A. Cardin, W. J. Nuttall, R. De Neufville, and J. Dahlgren. Extracting value from uncertainty: A methodology for engineering systems design. In INCOSE, 2007.

A. K. Cerbowski and J. W. Raymond. Operationally responsive space: A new defense business model. Parameters, US Army War College Quarterly, Summer 2005:10, 2005.

B. Chapman. Space Warfare and Defense: A Historical Encyclopedia and Research Guide. ABC-CLIO Inc, 2008.

D. Chattopadhyay, A. M. Ross, and D. H. Rhodes. Demonstration of system of systems multi-attribute tradespace exploration on a multi-concept surveillance architecture. In 7th Conference on Systems Engineering Research, Loughborogh, UK, 2009.

P. D. Childs, S. H. Ott, and A. J. Triantis. Capital budgeting for interrelated projects: A real options approach. Journal of Financial and Quantitative Analysis, 33(3):30, 1998.

K. Compton and S. Hauck. Flexibility measurement of domain-specific reconfigurable hardware. In ACM/SIGDA Symposium on Field-Programmable Gate Arrays, pages 115–161, 2004.

K. Corcoran. Higher eyes in the sky: The feasibility of moving AWACS and JSTARS functions into space. Master's thesis, Air University, 2000.

M. Davis. Future space based radar technology needs for surveillance. In AIAA/ICAS International Air and Space Symposium, Dayton, OH, 2003.

R. De Neufville. Uncertainty management for engineering systems planning and design. In ESD Symposium, Cambridge, MA, 2002.

R. DeLap. Recent and current air force space based radar efforts. In IEEE Aerospace Conference, Aspen, CO, 1999.

Department of Defense. The plan for operationally responsive space. Technical report, U.S. Government, 17 April 2007.

J. E. Derleth. Multi-Attribute Tradespace Exploration and its Application to Evolutionary Acquisition. PhD thesis, Massachusetts Institute of Technology, 2003.

J. Elster and G. Loewnstein. Utility from memory and anticipation. In G. Loewenstein and J. Elster, editors, Choice Over Time. Russell Sage Foundation, New York, 1992.

J. Enright, C. Jilla, and D. Miller. Modularity and spacecraft cost. Journal of Reducing Space Mission Cost, 1:133–158, 1998.

W. J. Fabrycky. Life Cycle Cost and Economic Analysis. Prentice-Hall, NJ„ 1991.

S. Finkelstein and S. H. Sanford. Learning from corporate mistakes: The rise and fall of iridium. Organizational Dynamics, 29(2):10, 2000.

B. J. Fram. The case for operationally responsive space. In 5th Responsive Space Conference, Los Angeles, CA, 2007.

E. Fricke and A. P. Schulz. Design for changeability: Principles to enable changes in systems throughout their entire lifecycle. Wiley Periodicals, Inc, 8(4), 2005.

Government Accounting Office. DoD needs a departmentwide strategy for pursuing low-cost, responsive tactical space capabilities. Technical Report GAO-06-425, U.S. Government, 2006.

Government Accounting Office. Dod is making progress to rapidly deliver low cost space capabilities, but challenges remain. Technical Report GAO-08-516, U.S. Government, 2008.

M. Griffin. Systems engineering and the two cultures of engineering. Boeing Lecture, Purdue University, 2007.

A. Ibanez. Valuation by simulation of contingent claims with multiple early exercise opportunities. Mathematical Finance, 14(2):27, 2004.

Iridium. Iridium satellite. Technical report, Iridium Satellite LLC, spider.ipac.caltech.edu, 22 April 2009. Picture.

© 2009 Massachusetts Institute of Technology

References (2)

Jet Propulsion Laboratory. Galileo at Io. Technical report, JPL, http://www.nasaimages.org, May 3 1996. Picture.

J. Jiao, T. W. Simpson, and Z. Siddique. Product family design and platform-based product development: a state-of-the-art review. Journal of Intelligent Manufacturing, page 25, 2007.

D. Kahneman and A. Tversky. Prospect theory: An analysis of decision under risk. In D. Kahneman and

A. Tversky, editors, Choices, Values, and Frames, pages 17–43. Cambridge University Press, Cambridge, 2000.

K. Kalligeros. Using real options for engineering systems design: framework, applicability and limitations. page 22, 2004.

K. Kalligeros. Platforms and Real Options in Large-Scale Engineering Systems. PhD thesis, Massachusetts Institute of Technology, 2006.

R. L. Keeney and H. Raiffa. Decisions with Multiple Objectives. Cambridge University Press, Cambridge, 1993.

J. E. Kelley and W. R. Morgan. Critical-path planning and scheduling. In AFIPS Joint Computer Conferences, Boston, MA, 1959. AMC.

A. Khajavirad and J. J. Michalek. A single-stage gradient-based approach for solving the joint product family platform selection and design problem using decomposition. In International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, page 17, 2007.

K. R. MacCrimmon and C. A. Ryavec. An analytical study of the pert assumptions. Operations Research, 12(1):21, 1964.

G. T. Mark. Incorporating flexibility into system design: a novel framework and illustrated developments. Master's thesis, Massachusetts Institute of Technology, 2005.

H. E. McCurdy. Faster, Better, Cheaper: Low-Cost Innovation in the U.S. Space Program. Johns Hopkins University Press, Baltimore, MD, 2001.

H. L. McManus. Space system architecture. Technical report, Massachusetts Institute of Technology, Oct 12, 2004 2004.

H. L. McManus and D. E. Hastings. A framework for understanding uncertainty and its mitigation and exploitation in complex systems. In INCOSE, page 20, Rochester NY, 2005.

National Aeronautics and Space Administration. Defense support program (DSP) satellite block ii computer rendering. Technical Report S91-50473, NASA, http://www.nasaimages.org, 1991. Picture.

J. Nickel, A. M. Ross, and D. H. Rhodes. Cross-domain comparison of design factors in system design and analysis of space and transportation systems. In 6th Conference on Systems Engineering Research, Los Angeles, CA, 2008.

R. Nilchiani. Measuring Space Systems Flexibility: A Comprehensive Six-element Framework. PhD thesis, Massachusetts Institute of Technology, 2005.

© 2009 Massachusetts Institute of Technology

References (3)

A. Olewnik and K. Lewis. A depiction support framework for flexible system design. Journal of Engineering Design, 17(1):23, 2006.

A. Qureshi, J. T. Murphy, B. Kuchinsky, C. C. Seepersad, K. L. Wood, and D. D. Jensen. Principles of product flexibility. In ASME 2006 International Design Engineering Technical Conference and Computers and Information in Engineering Conference, Philadelphia PA, 2006.

P. K. P. Rajan, M. Van Wie, M. I. Campbell, K. L. Wood, and K. N. Otto. An empirical foundation for product flexibility. Elsevier Ltd, 26(4):34, 2005.

M. G. Richards, L. Viscito, A. M. Ross, and D. E. Hastings. Distinguishing attributes for the operationally responsive space paradigm. In Responsive Space 6 Conference, Los Angeles, CA, 2008.

C. J. Roberts, M. G. Richards, A. M. Ross, D. H. Rhodes, and D. E. Hastings. Scenario panning in dynamic multi-attribute tradespace exploration. In IEEE International Systems Conference, Vancouver, Canada, 2009.

A. M. Ross. Multi-attribute tradespace exploration with concurrent design as a value-centric framework for space systems architecture and design. Master's thesis, Massachusetts Institute of Technology, 2003.

A. M. Ross. Managing Unarticulated Value: Changeability in Multi-Attribute Tradespace Exploration. PhD thesis, Massachusetts Institute of Technology, 2006.

A. M. Ross and D. H. Rhodes. Using natural value-centric time scales for conceptualizing system timelines through epoch-era analysis. In INCOSE 2008, Utrecht, the Netherlands, 2008.

A. M. Ross, D. E. Hastings, J. M. Warmkessel, and N. P. Diller. Multi-attribute tradespace exploration as a front-end for effective space system design. AiAA Journal of Spacecraft and Rockets, 2004.

A. M. Ross, H. L. McManus, A. Long, M. G. Richards, D. H. Rhodes, and D. E. Hastings. Responsive systems comparison method: Case study in assessing future designs in the presence of change. In AIAA Space 2008, San Diego, CA, 2008a.

A. M. Ross, D. H. Rhodes, and D. E. Hastings. Defining changeability: Reconciling flexibility, adaptability, scalability, modifiability, and robustness for maintaining lifecycle value. Systems Engineering, 11(3): 246–262, 2008b.

A. M. Ross, D. H. Rhodes, and D. E. Hastings. Using pareto trace to determine system passive value robustness. In IEEE International Systems Conference, Vancouver, Canada, 2009.

J. H. Saleh. Weaving Time into System Architecture: New Perspectives on Flexibility, Spacecraft Design Lifetime, and On-orbit Servicing. PhD thesis, Massachusetts Institute of Technology, 2002.

J. H. Saleh and D. Gregory. Responsive space: Concept analysis, critical review, and theoretical framework. In AIAA Space 2007, Long Beach, CA, 2007. AIAA.

J. H. Saleh, G. T. Mark, and N. C. Jordan. Flexibility: a multi-disciplinary literature review and a research agenda for designing flexible engineering systems. Journal of Engineering Design, 2008.

N. B. Shah, L. Viscito, J. M. Wilds, A. M. Ross, and D. E. Hastings. Quantifying flexibility for architecting changeable systems. In 6th Conference on Systems Engineering Research, Los Angeles, CA, 2008.

G. B. Shaw. The Generalized Information Network Analysis Methodology for Distributed Satellite Systems. PhD thesis, Massachusetts Institute of Technology, 1998.

E. Shuiabu, V. Thompson, and N. Bhuiyan. Entropy as a measure of operational flexibility. European Journal of Operational Research, 2004.

J. L. Smith and R. Thomspon. Managing a portfolio of real options: Sequential exploration of dependent prospects. Center for Energy and Environmental Policy Research, 2004.

T. J. Spaulding. Tools for evolutionary acquisition: A study of multi-attribute tradespace exploration (mate) applied to the space based radar (sbr). Master's thesis, Massachusetts Institute of Technology, 2001.

D. P. Thunnissen. Balancing cost, risk, and performance under uncertainty in preliminary mission design. In Space 2004, San Diego, CA, 2004.

E. B. Tomme. The strategic nature of the tactical satellite. Air University, 2006.

L. Viscito and A. M. Ross. Combining pareto trace and filtered outdegree as a metric for identifying valuably flexible designs. In 7th Conference on Systems Engineering Research, Loughborough, UK, 2009.

M. A. Walton. Managing Uncertainty in Space Systems Conceptual Design Using Portfolio Theory. PhD thesis, Massachusetts Institute of Technology, 2002.

D. P. Wickert. Space based radar- system architecture design and optimization for a space based replacement to awacs. Master's thesis, Massachusetts Institute of Technology, 1997.

A. G. Williams, W. Harding, and H. Hagemeier. Assessment of responsive replenishment launch for constellation management. In AIAA, 1999.

J. M. Wilson. Gantt charts: A centenary appreciation. European Journal of Operational Research, 149(2):7, 2003.

© 2009 Massachusetts Institute of Technology