Systems Engineering Advancement Research Initiative

Combining Pareto Trace with Filtered Outdegree as a Metric for Identifying Valuably Flexible Systems

7th Conference on Systems Engineering Research
Loughborough University, UK
April 21, 2009

Lauren Viscito,
Research Assistant, Aeronautics & Astronautics

Debarati Chattopadhyay,
Research Assistant, Aeronautics & Astronautics

Adam M. Ross, Ph.D.,
Research Scientist, Engineering Systems Division

Massachusetts Institute of Technology

Agenda

- Introduction
- Flexibility
- Multi-Attribute Tradespace Exploration
- Epoch-Era Analysis
  - Pareto Trace Designs
  - Filtered Outdegree Designs
- Synthesis: Value Weighted Filtered Outdegree
- Conclusions

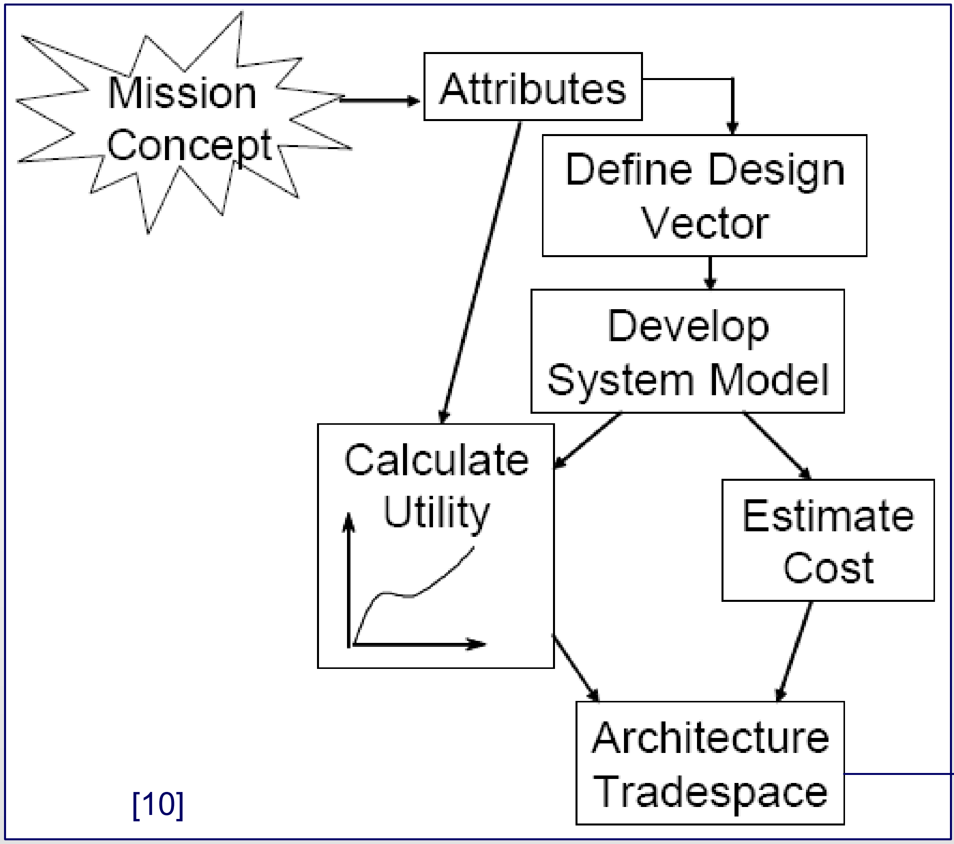
Flexibility

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.

- Uncertainty in future system context → risk that system will not deliver value [1]
  - Flexibility is a risk mitigation strategy [2,3]
  - Takes advantage of opportunities from uncertainty
  - Flexibility may be added to the design process, or to the end product [4]
- Practical and useful way to measure flexibility lacking in tradespace exploration
  - Measuring flexibility is often domain specific or descriptive in nature [5,6,7,8]
  - Assigning a dollar value is not suitable for explicitly trading designs [9]

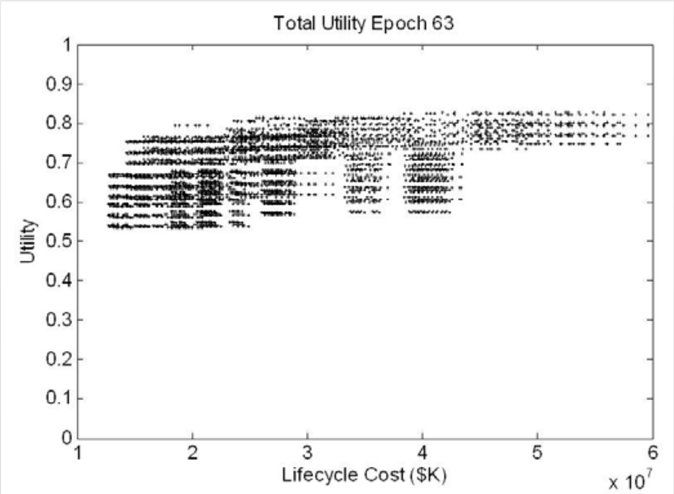
Identifying valuably flexible designs is essential for trading flexibility.
Need a metric tailored for tradespace exploration design methods.

Multi-Attribute Tradespace Exploration (MATE)



1. Specify value proposition
   - Interview decision-maker(s)
   - Create a list of attributes
   - Elicit utility curves
2. Enumerate design vector
3. Develop system model
4. Evaluate candidate architectures in tradespace

[10,11]



Application of decision analysis and utility theory to model and simulation-based design

Epoch-Era Analysis for Generating Future Scenarios

Compare Alternatives

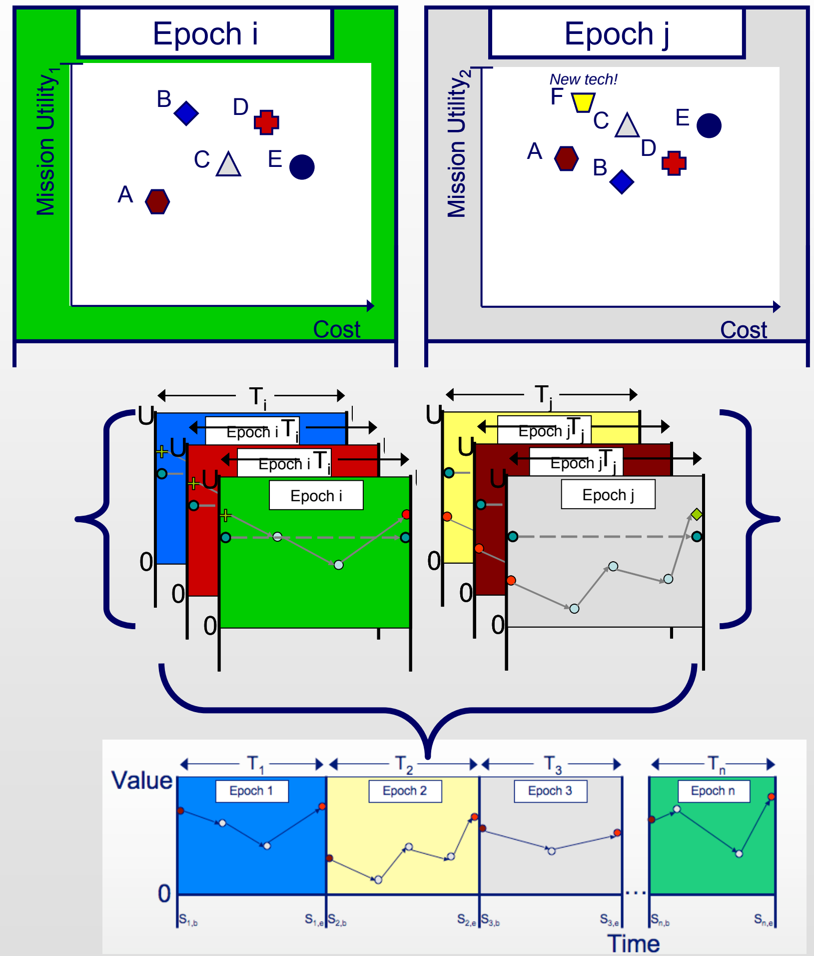
Static tradespaces compare alternatives for fixed context and needs (per Epoch)

Define Epochs

Epoch set represents potential fixed contexts
Calculate Filtered Outdegree and Pareto Trace [14,15]

Construct Eras

Eras represent ordered epoch series for analyzing system evolution strategies [12,13]



Parameterizing future contexts allows for generating ensembles of scenarios

Satellite Radar System Case Application

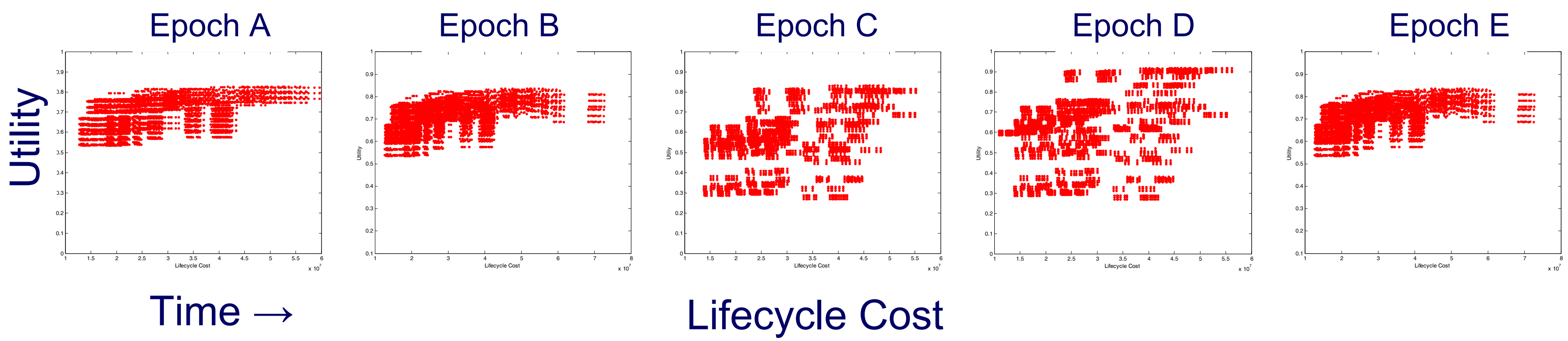
Epoch Variable
Utility Expectations
Radar Technology
Communications Infrastructure
AISR Assets
Operations Plan
Jamming Environment

Satellite Monostatic Radar System [16]

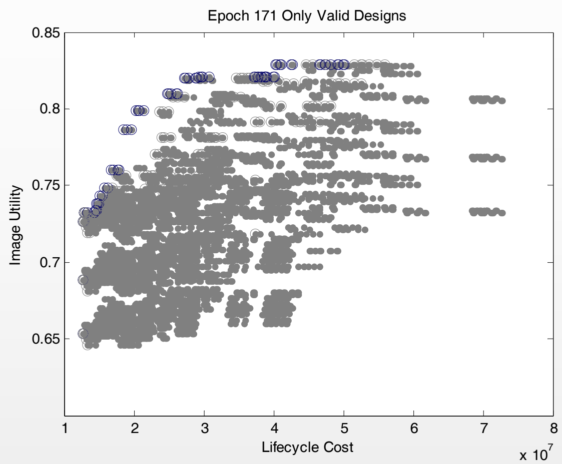
Design Variable
Peak Transmit Power
Radar Bandwidth
Antenna Area
Satellite Altitude
Constellation Design
Communications Downlink
Tactical Downlink
Maneuver Package
Constellation Option

Attributes

Resolution	Min Discernable Velocity
Field of View	Min Radar Cross Section
Imaging Latency	Number of Target Boxes
Revisit Gap Time	Tracking Latency
Self Geolocation Accuracy	Track Life
Number of Targets/ Pass	Target Acquisition Time



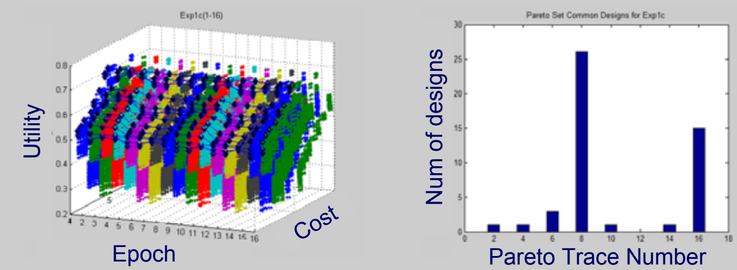
Calculating Pareto Trace to Uncover Value Robust Designs



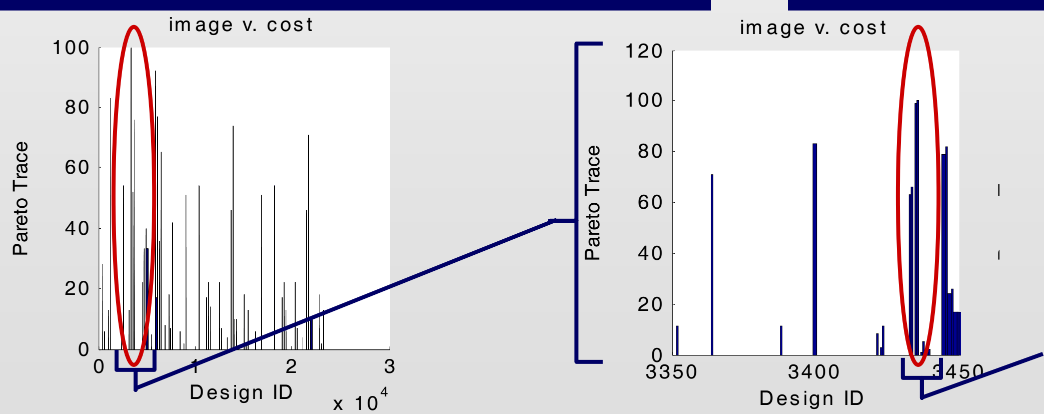
Find non-dominated solutions within a given epoch (Pareto Set)

Pareto Trace Number

Pareto Sets containing design
(measure of passive robustness)



Across many epochs, track number of times solution appears in Pareto Set



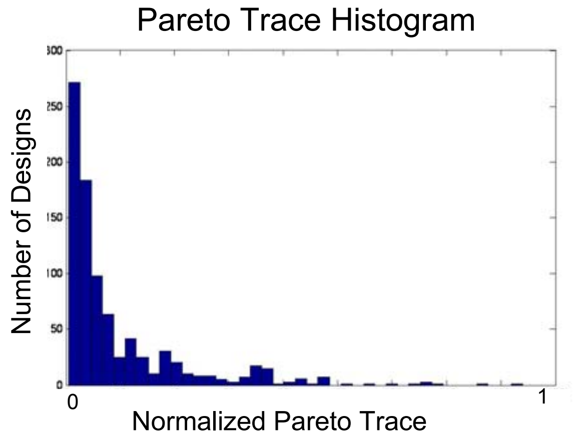
Identify designs with high Pareto Trace for further investigation

Design 3435 is in 67% of Pareto Sets

Higher Pareto trace designs are more passively value robust

High Pareto Trace Designs

- 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



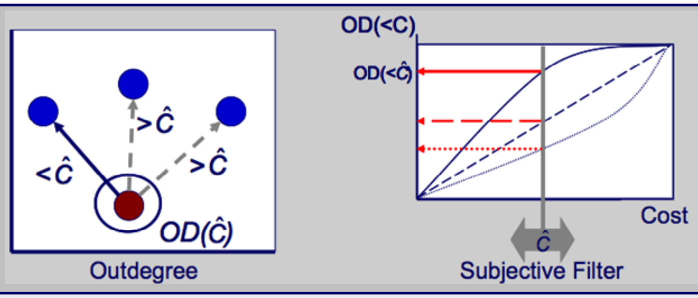
Design Number	Normalized Pareto Trace	Total Utility Epoch A	Epoch B	Epoch C	Epoch D	Epoch E
3435	0.69	0.75	0.75	0.57	0.66	0.75
3447	0.55	0.76	0.76	0.63	0.73	0.76
3555	0.56	0.82	0.82	0.81	0.90	0.82
6027	0.62	0.76	0.76	0.55	0.65	0.76
6039	0.53	0.76	0.76	0.61	0.71	0.76
6147	0.53	0.81	0.81	0.81	0.90	0.81

High Pareto Trace designs are Value Robust across many epochs, but are not highly changeable.

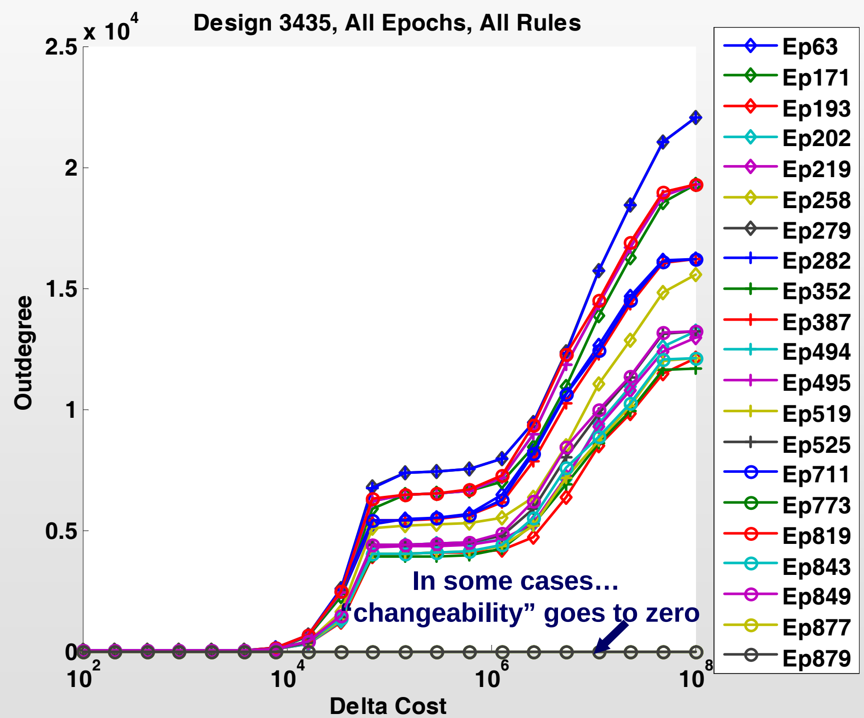
Calculating Filtered Outdegree to Uncover Changeable Designs

Filtered Outdegree

outgoing arcs from design at acceptable "cost" (measure of changeability)



Variation in design "changeability" in response to context change



Defined 8 System Transition Paths (Rules)

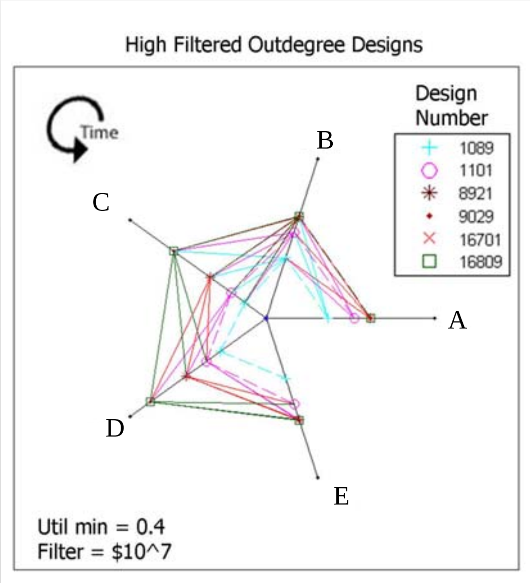
1. Redesign *(Design Phase)*
2. Redesign *(Build Phase)*
3. Redesign *(Test Phase)*
4. Add satellites to constellation *(Ops Phase)*
5. Alter altitude with on-orbit fuel *(Ops Phase)*
6. Alter altitude through tug *(Ops Phase)*
7. Alter inclination with on-orbit fuel *(Ops Phase)*
8. Alter inclination through tug *(Ops Phase)*

One can identify "changeable" designs and design choices (real options) by determining the filtered outdegree at a given acceptable transition "cost" threshold

High Filtered Outdegree Designs

- 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

Design Number	FOD Filter is $10^7	Total Utility Epoch A	Epoch B	Epoch C	Epoch D	Epoch E
1089	188	0.62	0.63	0.49	0.60	0.63
1101	359	0.72	0.72	0.55	0.66	0.72
8921	488	0.77	0.78	0.65	0.75	0.78
9029	278	0.77	0.78	0.81	0.91	0.78
16701	437	0.77	0.78	0.65	0.75	0.78
16809	263	0.77	0.78	0.81	0.91	0.78



High Filtered Outdegree designs are very changeable, but may cost more due to included change mechanisms.

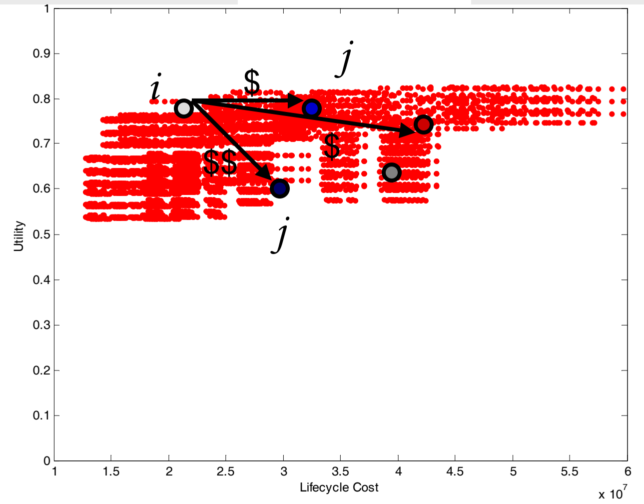
Value Weighted Filtered Outdegree (VWFO)

- 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
  - Considers designs across changes in context

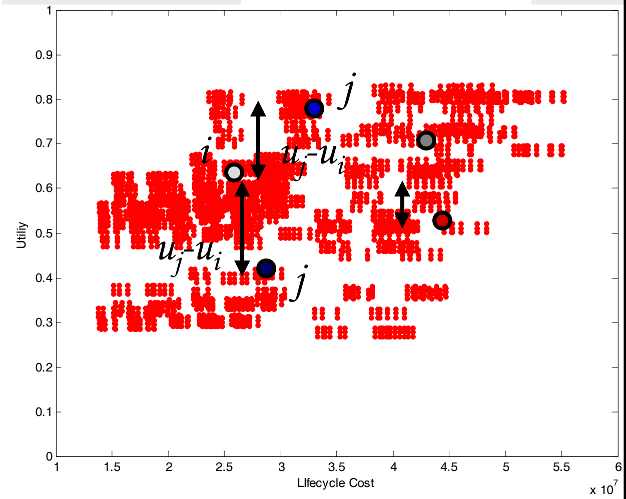
$$VWFO_i^k = \frac{1}{N}\sum_{j=1}^{N}[\text{sgn}(u_j^{k+1} - u_i^{k+1}) * Arc_{i,j}^k]$$

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

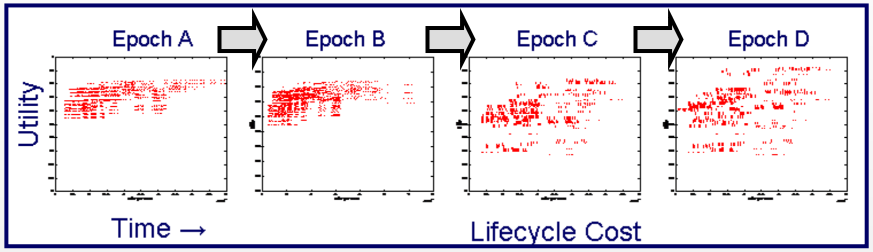
Epoch A (k)



Epoch B (k+1)

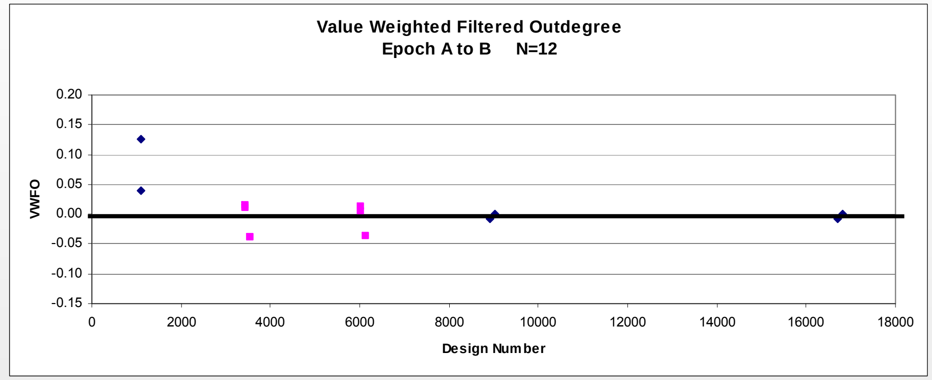


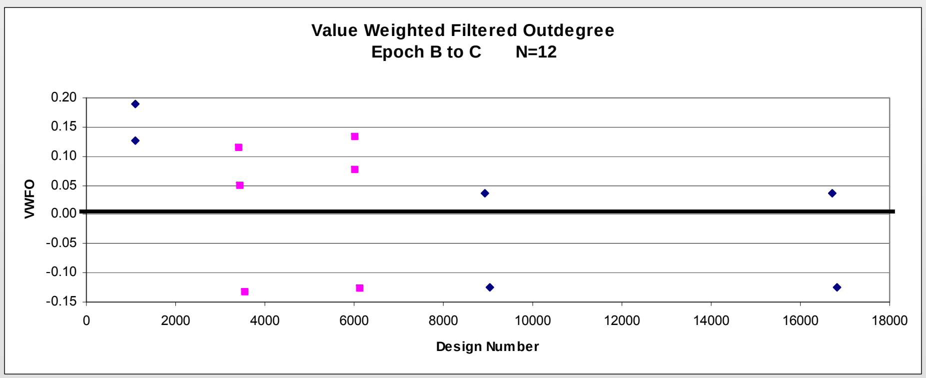
VWFO for Selected Designs

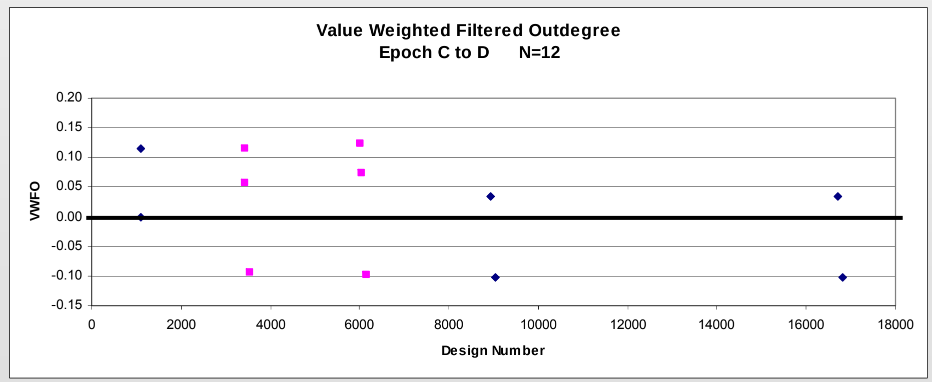


N=12

FOD
NPT

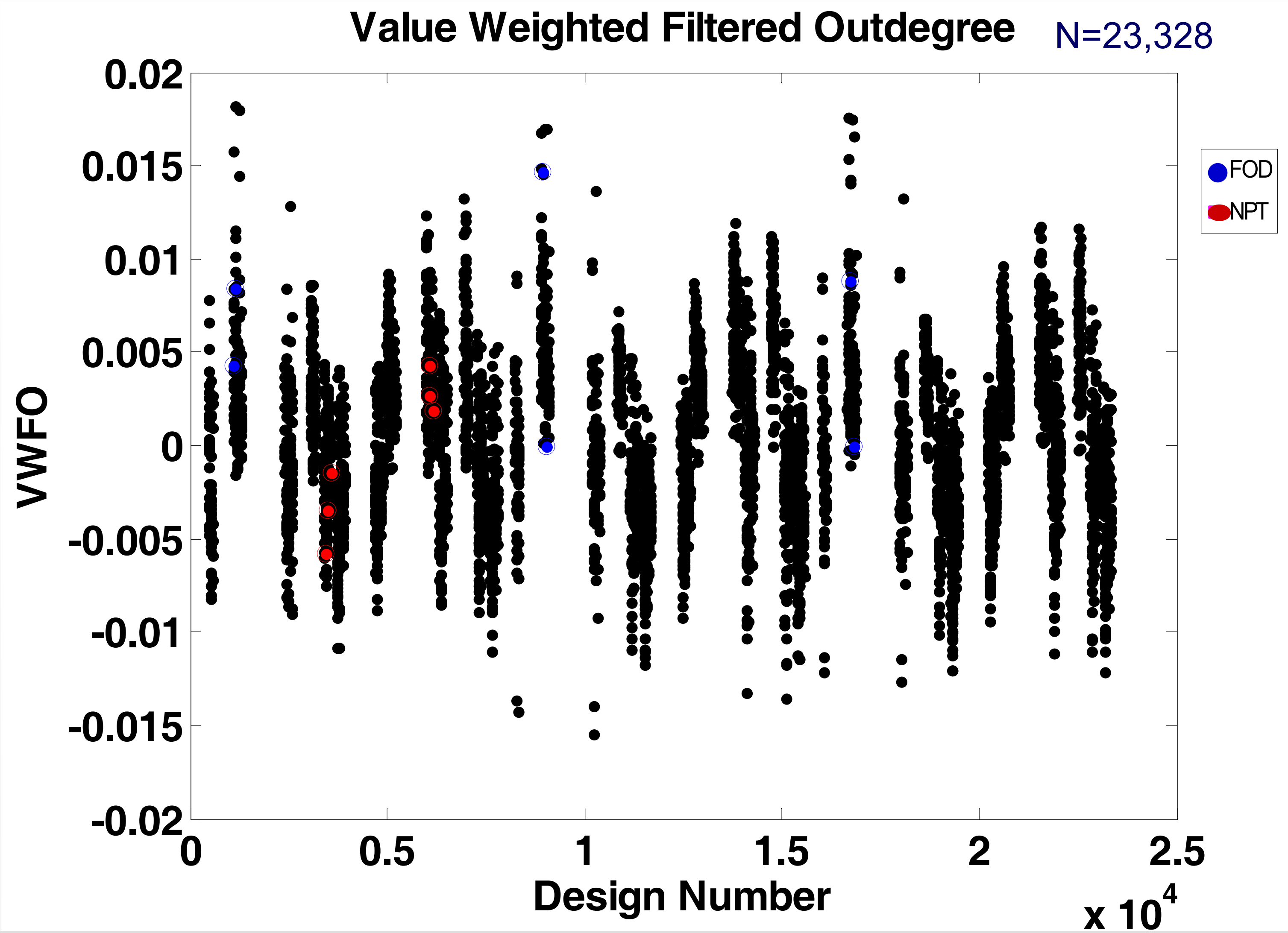




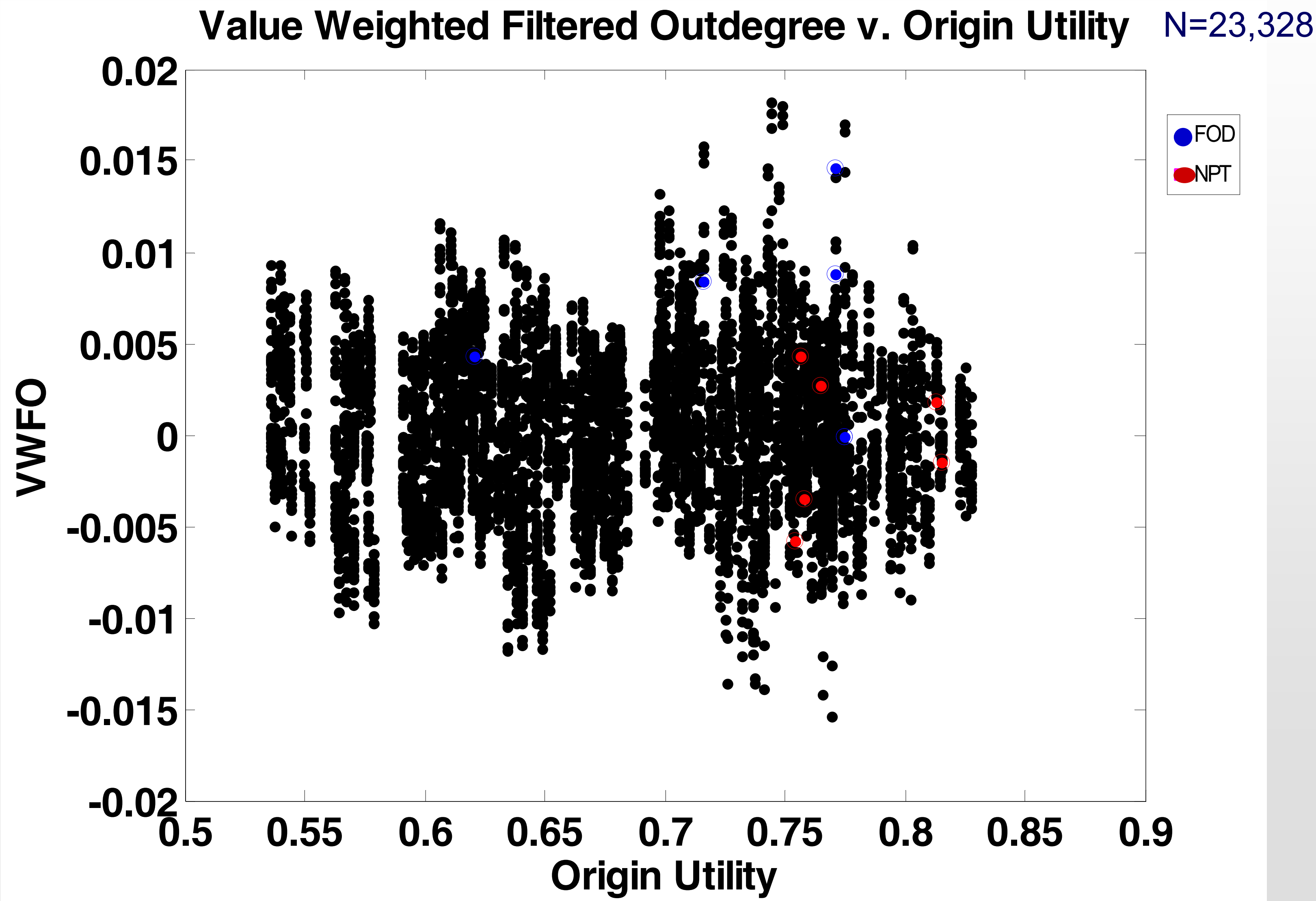


Designs with high magnitude VWFO are highly changeable and positive VWFO indicates designs that are valuably flexible.

VWFO for Full Tradespace

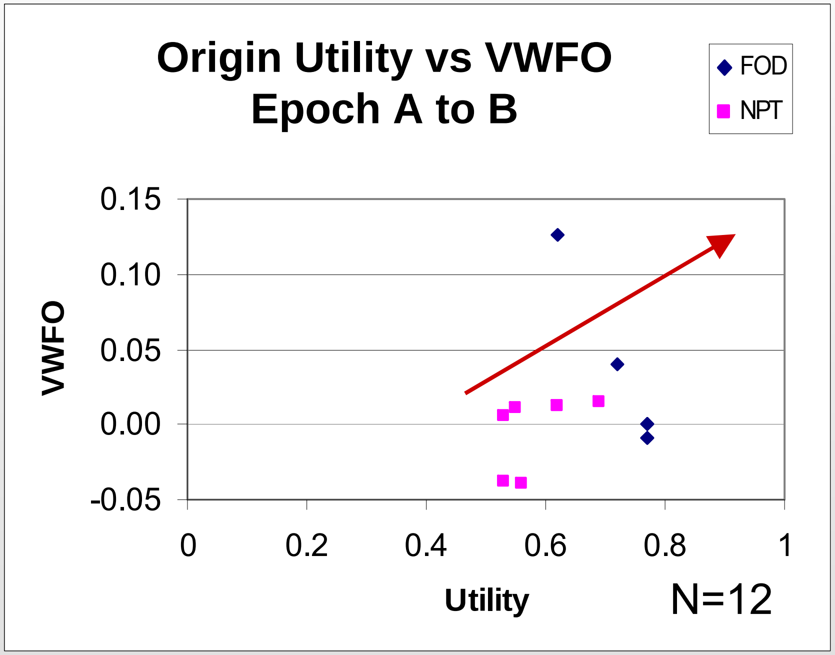


VWFO vs. Design Utility for Full Tradespace



Conclusions

- VWFO identifies designs that are valuably flexible
- Intended as a heuristic for designers to trade flexibility
- Metric considers:
  - Changeability of designs
  - Utility change of designs
  - Context changes
- Future Work
  - Apply to full tradespace
  - Apply to different case study
  - Aggregate metric over era



Value Weighted Filtered Outdegree is a practical way to screen tradespace for valuably flexible designs.

References

[1] Ross, A.M. (2006), Managing Unarticulated Value: Changeability in Multi-Attribute Tradespace Exploration, Ph.D. thesis, Massachusetts Institute of Technology.

[2] Nilchiani, R. (2005), Measuring Space Systems Flexibility: A Comprehensive Six-element Framework, Ph.D. thesis, Massachusetts Institute of Technology.

[3] Banerjee, P. & de Weck, O.L. (2004), “Flexibility Strategy- Valuing Flexible Product Options,” in “INCOSE/ICSE Conference on Synergy Between Systems Engineering and Project Management,” Las Vegas, NV: INCOSE, p. 8.

[4] Saleh, J.H., Mark, G.T. & Jordan, N.C. (2008), “Flexibility: a multi-disciplinary literature review and a research agenda for designing flexible engineering systems,” Journal of Engineering Design , p. 17.

[5] Compton, K.&Hauck, S. (2004), “Flexibility Measurement of Domain-Specific Reconfigurable Hardware,” in “ACM/SIGDA Symposium on Field-Programmable Gate Arrays,” pp. 115–161.

[6] Ajah, A.N., Herder, P.M., Grievink, J. & Weijnen, M.P.C. (2005), “Framework for Proper Integration of Flexibility in Conceptual Designs of Energy and Industrial infrastructures,” in P. L & E. A (eds.), “European Symposium on Computer Aided Process Engineering,”.

[7] Olewnik, A. & Lewis, K. (2006), “A Desicion Support Framework for Flexible System Design,” Journal of Engineering Design 17(1), p. 23.

[8] Rajan, P.K.P., Van Wie, M., Campbell, M.I., Wood, K.L. & Otto, K.N. (2005), “An empirical foundation for product flexibility,” .

[9] de Neufville, R. (2002), “Uncertainty Management for Engineering Systems Planning and Design,” in “ESD Symposium,” Cambridge, MA.

[10] Ross, A.M., Hastings, D.E.,Warmkessel, J.M. & Diller, N.P. (2004), “Multi-Attribute Tradespace Exploration as a Front-End for Effective Space System Design,” AIAA Journal of Spacecraft and Rockets .

[11] Ross, A.M. (2003), 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.

[12] Roberts, C.J., Richards, M.G., Ross, A.M., Rhodes, D.H. & Hastings, D.E. (2009), “Scenario Panning in Dynamic Multi-Attribute Tradespace Exploration,” in “IEEE International Systems Conference,” Vancouver, Canada.

[13] Ross, A.M. & Rhodes, D.H. (2008), “Using Natural Value-centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis,” in “INCOSE 2008,” Utrecht, the Netherlands.

[14] Ross, A.M., Rhodes, D.H. & Hastings, D.E. (2009), “Using Pareto Trace to Determine System Passive Value Robustness,” in “IEEE International Systems Conference,” Vancouver, Canada.

[15] Ross, A.M., Rhodes, D.H. & Hastings, D.E. (2008), “Defining Changeability: Reconciling Flexibility, Adaptability, Scalability, Modifiability, and Robustness for Maintaining Lifecycle Value,” Systems Engineering 11(3), pp. 246–262.

[16] Ross, A.M., McManus, H.L., Long, A., Richards, M.G., Rhodes, D.H. & Hastings, D.E. (2008), “Responsive Systems Comparison Method: Case Study in Assessing Future Designs in the Presence of Change,” in “AIAA Space 2008,” San Diego, CA.

SEA RI

Systems Engineering Advancement Research Initiative

Questions?

viscitol@mit.edu