ADAM M ROSS, ESD PhD 2006

Title: Managing Unarticulated Value: Changeability in Multi-Attribute Tradespace Exploration

Motivation: Cost committal at the beginning of the design process makes early attention a high leverage point for improving system cost. Premature reduction of a tradespace during Conceptual Design may inappropriately restrict design considerations, leading to less valuable system choices. Coupling value-centric decision-making with broad technical tradespace exploration, Multi-Attribute Tradespace Exploration (MATE) has proven to be a useful framework for capturing cost-benefit knowledge over a large space of design options. Ongoing research into MATE has revealed a promising potential for its use as a framework to understand unarticulated value propositions arising from dynamic issues, including changing preferences, incomplete information, and learning. In order to create sustainably valuable systems, designers must understand both articulated and unarticulated, or not explicitly communicated, value propositions from a potentially dynamic stakeholder set. Discussions with industry and academia, through an LAI/AF sponsored workshop, MIT ESD symposia, as well as direct site visits by this researcher motivated the present work. Quantification of system properties (e.g. flexibility), as well as understanding dynamic value effects on Conceptual Design tradespaces, would be of high value to the design and decision-making community and is presently poorly understood.

Research Questions: Within the context of the MATE framework:
(Q1) What are the relationships between *flexibility, adaptability, robustness, and scalability* for aerospace systems and how do they relate to *unarticulated value*?
(Q2) How can these ilities be *quantified and/or used as decision metrics* when exploring tradespaces during Conceptual Design?

Research Design: In order to address these two questions, the research design involves four main thrusts: knowledge capture and synthesis, theory development, computer experiments, and case applications. Knowledge capture and synthesis builds off of prior work in value-centric tradespace exploration. Theory development seeks to build new knowledge from foundational principles, informed by insights garnered through the other three thrusts. Experiments use computer models to seek to isolate and understand complex quantitative relationships in a tradespace study, allowing for direct feedback between hypothesis generation and testing. Case applications seek to apply the research to more "realistic" and "messy" problems in order to better understand the limits, applicability, and deployability of the research.

Research Contributions: The research contributions fall into six main categories:

1. A unified definition of flexibility, adaptability, robustness, and scalability.
2. Quantification of flexibility, adaptability, robustness, and scalability.
3. A framework for capturing and representing unarticulated value.
4. A framework for discovering "best" solutions in multi-decision maker tradespaces.
5. A framework for considering "design for changeability."
6. Insight into real world aerospace system relevance through case applications.

Dissertation Structure:
The structure of the dissertation is as follows: **Chapter 2** provides a brief overview of topics covered in the literature that had significant influence over the synthesis of ideas in the research.

Not all literature referenced in the chapter will be explicitly addressed in the main body, nor is the listed literature exhaustive of the influencing body of knowledge that resulted in this work. **Chapter 3** provides a short overview of the static MATE value-centric design process, with extensive referencing to (Ross 2003) for more detailed discussions. MATE provides the foundation from which the current research builds. **Chapter 4** expands the restricted view of value presented in classical MATE analysis to include "unarticulated" value. **Chapter 5** introduces the concept of time, its relation to decision-making and design, and motivation for incorporating temporal analysis in order to deliver sustained value. **Chapter 6** defines the system properties, or "ilities," of interest in this research: flexibility, adaptability, scalability, modifiability, and robustness. **Chapter 7** applies numerical computer experiments to changing tradespaces in an effort to deduce quantitative methods for capturing system properties in practice. **Chapter 8** synthesizes the previous chapters and introduces dynamic MATE analysis. A running example applied to the X-TOS space system is provided to elucidate concepts and methods. **Chapter 9** and **Chapter 10** apply the dynamic MATE analysis at varying levels of fidelity to real world systems: the Joint Direct Attack Munition (JDAM) system and the Terrestrial Planet Finder (TPF) system. **Chapter 11** provides a discussion of the research, including limitations, implications, and potential application areas. **Chapter 12** summarizes the findings and suggests avenues for future work. **Chapter 13** lists references from the main text. **Chapter 14** is a notation glossary, which, though not exhaustive, attempts to highlight key variables used in the analysis. The remainder of the thesis contains various **Appendices** containing supporting data, templates, and references a reader may find of interest.

<u>Results</u>: Answering the Research Questions

(Q1) What are the relationships between flexibility, adaptability, robustness, and scalability for aerospace systems and how do they relate to unarticulated value?
(A1) The ilities relate to the changeability mapping of design variables $\{DV^N\}$ to attributes $\{X^M\}$ (decision metrics) through a transition rule set $\{R^K\}$; unarticulated value can be captured as classes of attributes, motivating the transition rules.

(Q2) How can these ilities be quantified and/or used as decision metrics when exploring tradespaces during Conceptual Design?
(A2) Changeability can be quantified using tradespace network-derived Filtered Outdegree, OD($<\hat{C},\hat{t}$), passive robustness using Pareto Trace number; together these can be used in System Era tradespace path analysis to determine "best" dynamic strategies to achieve value robustness.

<u>Changeability and Robustness Revisited</u>

One of the benefits of taking a value-centric perspective on the system design problem is that it focuses attention on what is important and what can be done in order to achieve it: value-space and design-space. Flexibility and adaptability are the two types of design-space change, in terms of externally motivated and internally motivated change, respectively. Scalability and modifiability are the effects of the change on the tradespace, in terms of level of a tradespace parameter and membership in the tradespace parameter set, respectively. (In general the tradespace parameters of interest are the attributes since they drive value. Attributes can be design variables if the decision maker derives value from the design variables themselves.) Each of these ilities are aspects of changeability, which captures both objective (whether can change) and subjective (acceptable “cost” for change) aspects. Value robustness is the perception that a system continues to deliver value in spite of changes in its context or design parameters.

Unarticulated value is wrapped into the MATE framework in terms of classes of attributes. When analyzing the system, both articulated, or class 0, attributes and possible unarticulated, or class 1-3, attributes are calculated and mapped into the changeability analysis. Movement of attributes from class 1-3 to class 0 represents articulation of value and the designer can take steps to reduce the cost of the system change response to the new value perceptions. Designs quantified as having high outdegree are those which are most changeable. The subjective cost and time thresholds, however, reduce the actual perceived outdegree of a design for a particular decision maker.

One of the goals of a system designer is to maximize value delivery at efficient levels of resource expenditure. Pareto Tracing provides a mechanism for the analyst to discover and quantify designs that are passively most value robust. A design with high Pareto Trace is one that appears in many Pareto Sets across various Epochs, or change scenarios. These designs can become “attractors” for future scenarios, as a goal state for change pathways. Additionally, real-space analysis of the Pareto Trace gives system designers insight into the most value-delivering and efficient combination of design parameters in the face of changing contexts. Figure 1 below gives examples of the quantified changeability and robustness for several X-TOS designs.

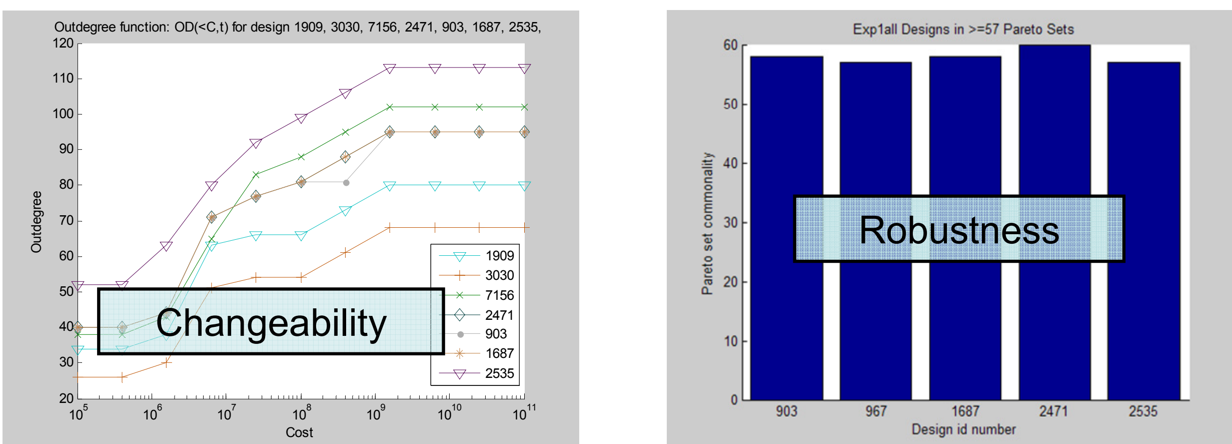

Figure 1 Changeability and passive value robustness for selected X-TOS designs

Summary of Key Research Contributions

The key contributions of this research can be summarized into six main categories.

1. A unified definition of six system properties (ilities)

The six ilities considered in this thesis are shown to be different aspects of the same concept: changeability. (Figure 2 below reviews the concept of changeability.) Flexibility and adaptability relate to the origin of the change agent: external or internal to the system boundary, respectively. Scalability and modifiability relate to changes in levels or sets of system parameters, respectively. Robustness cast as “value robustness” relates to maintaining value delivery in spite of changes within or without the system. Robustness can be pursued either through passive robustness (choosing a good design that does not need to change), or active robustness (choosing a design that can be altered to continue to deliver value over time).

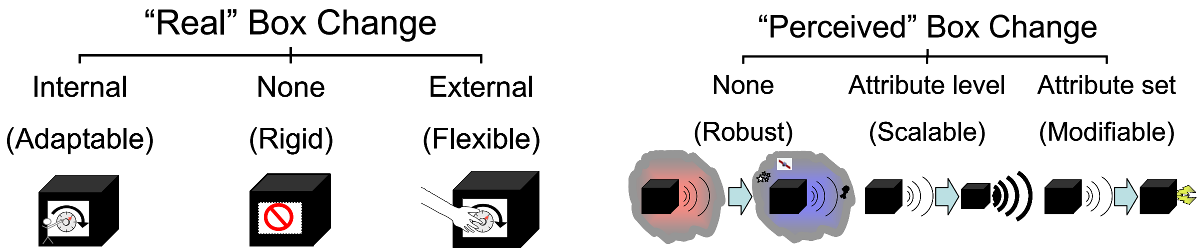

Figure 2 Aspects of changeability: adaptability, rigidity, flexibility, robustness, scalability and modifiability

2. Quantification of flexibility/adaptability/robustness/scalability/modifiability

As aspects of changeability, flexibility/adaptability/scalability/modifiability can be quantified as the Filtered Outdegree of a particular design in a tradespace network generated by transition rules (see Figure 3 below). The outdegree reflects the number of possible change paths from a design's current state to possible future states. The filter is the subjectively set acceptability threshold that varies from decision maker to decision maker, capturing the inherent subjectivity of changeability perception. Only paths "costing" less than the acceptability threshold are counted when determining the Filtered Outdegree. A change in subjective perceptions, increases in change mechanisms (transition rules), or decreases in cost for change all can increase the perceived changeability of a system.

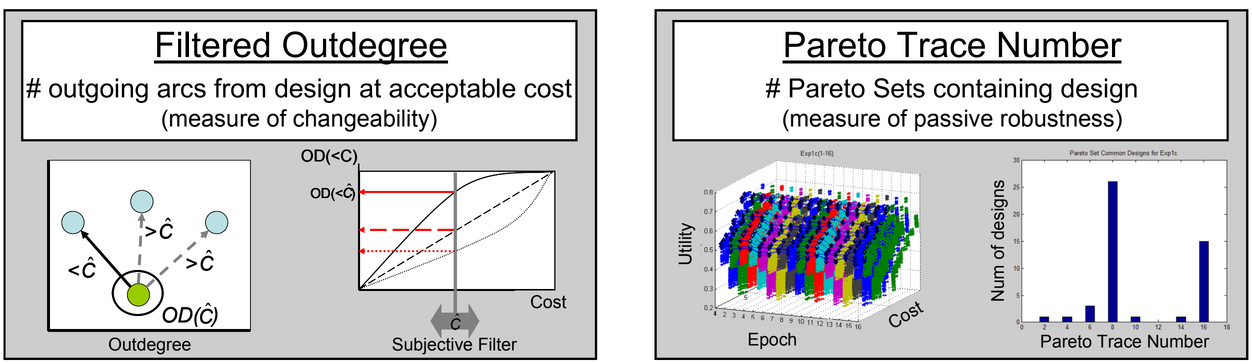

Figure 3 Filtered Outdegree and Pareto Trace Number definitions

Passive value robustness can be quantified as the Pareto Trace number, which is the number of Epochs (or scenarios) whose Pareto Set contains that particular design, reflecting the designs that have the most efficient utility for a given level of resource expenditure (see Figure 3). A relatively large Pareto Trace number implies a high passive robustness factor for a particular design and can be a function of excess capability, insensitivity to the particular change scenario, or a locally stable region in a tradespace.

3. Framework for representing unarticulated value

In addition to the typical articulated value, captured in explicit communication between decision makers and system designers, a spectrum of value exists. Unarticulated value includes those current and potential aspects of a system that result in value to a decision maker, but have not been explicitly communicated. Differentiating between the articulated and unarticulated value in terms of "cost to display" in the system results in five attribute classes (see Table 1 below). The "display" of an attribute means that the system "is" or "does" the attribute.

Table 1 Attribute class definitions

Class	Name	Property of Class	Cost to Display
0	Articulated Value	Exist and assessed	0
1	Free Latent Value	Exist, not assessed	0
2	Cheap Latent Value	Can exist by recombining class 0 and/or 1	Small
3	Accessible Value	Can be added through changing {DV} (scale or modify)	Small→large
4	Inaccessible Value	Cannot be added through changing {DV} (system too rigid)	Large→infinite

Class 0 attributes are the "articulated value" and include those value metrics that are explicitly used to design the system. These attributes are "free" to display since the system already addresses them. The rest of the classes are types of unarticulated value. Class 1 attributes are "free latent" value, representing aspects of a system already being displayed, but not asked for by the decision maker. If that attribute becomes value generating, it is "free" for the system to display it. Class 2 attributes are "cheap latent" value, representing aspects of the system that can be created through a simple recombination through an interpretation mechanism. The system itself does not require change, only the interpretation of the existing displayed attributes. Class 3 attributes are "accessible" value, representing attributes that could be displayed through a change to the system. The cost for the articulation of class 3 attributes ranges from cheap to expensive. Class 4 attributes are "inaccessible" value, representing attributes that cannot be displayed by the system due to excessive cost or the existence of constraints. These attributes are better displayed in a different system.

4. Framework for discovering "efficient" solutions for multi-stakeholder negotiations

The multi-decision maker tradespace exploration proposed in dynamic MATE results in a set of designs that can be used as the basis for negotiation. The single decision maker Pareto Set solutions represent the most "efficient" usage of resources for creating value for that particular decision maker. The Joint Pareto Set is the multi-decision maker analogue and captures the individual Pareto Set solutions as well as "compromise" solutions that trade between the decision makers. (Figure 4 below gives the Joint Pareto Set example from X-TOS analyzed in Chapter 7.)

Designs in Joint Pareto Set

DM1 Pareto Set   DM2 Pareto Set   Compromise Pareto Set

903	919	920	933	935	936	951	952	965	967	981
982	983	984	997	1687	1703	1735	1749	1751	1765	1767
1781	2471	2487	2501	2503	2519	2533	2535	2549	2551	2565
4511	4515	4531	4535	4536	4539	4540	4555	4556	4559	4560
4563	4564	4579	4580	4583	4584	4587	4588	4603	4604	4607
4608	4611	4612	4627	4628	4631	4632	4633	4707	4708	4727
4728	4747	4748	4771	4773	4795	4796	4797	5687	5691	5707
5711	5715	5731	5735	5739	5755	5759	5779	5783	5787	5803
5807	5809	5883	5903	5923	5947	5949	5971	5973	6863	6867
6883	6887	6891	6907	6911	6915	6931	6935	6939	6955	6959
6963	6979	6983	6985	7059	7079	7099	7123	7125	7147	7148
7149										

Joint Pareto size: 122 designs

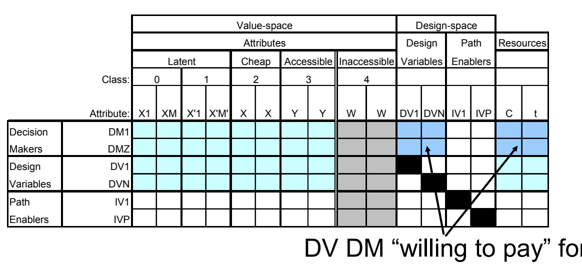

Figure 4 Example Joint Pareto Set for X-TOS, including overlapping "best" designs in white, and Design-Value Matrix used for analyzing cost-benefit distribution among decision makers

Knowledge of the structure of the tradespace, as well as the Joint Pareto Set enables decision makers to understand the key trades between their value propositions and whether an acceptable compromise solution can be found. The distribution of costs and benefits (resources and utility) can also be illustrated through this process, helping decision makers to discover key tensions in the interpersonal comparison of utility, which cannot be done in an arbitrary fashion. (See Figure 4 for a notional example using the Design-Value Matrix for distribution of costs and benefits.)

5. Framework for considering "Design for Changeability"

The usage of Design-Value Matrices, Rule-Effects Matrices, and Outdegree Assessments help focus the attention of designers on the effects of change on the value propositions of decision makers, as well as the effect on the system design parameters. (Figure 5 below: Design-Value Matrix.) Explicit attention to the creation of "Path Enablers" reveals design choices that create value not through their effect on attributes, but rather through their effect at enabling change (through the generation of additional change paths, or their reduction in cost of change path). The Path Enablers can be traced through their effects on design parameters to attributes and subsequently to the decision makers. In this way, designers can better understand "who might care about modularity" and therefore be willing to pay for it. The change enabling nature of these concepts can be used as a strategy for reducing long run change costs within an organization, as shown in the JDAM case application.

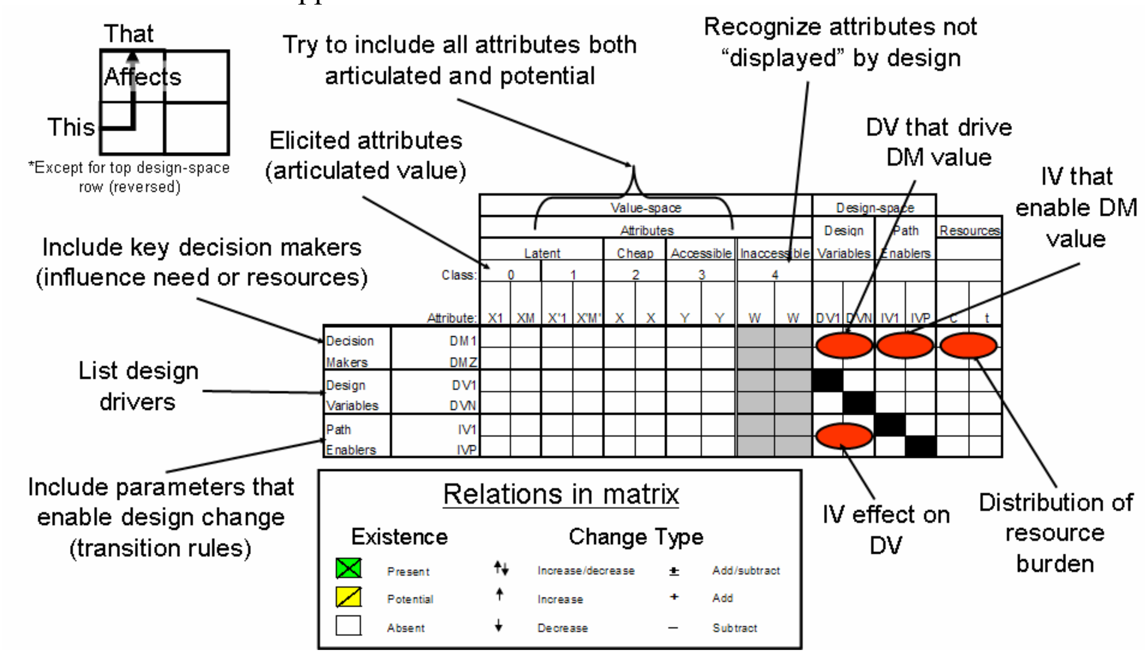

Figure 5 Design-Value Matrix defined

6. Application of dynamic MATE to two real systems

The Joint Direct Attack Munition (JDAM) and the Terrestrial Planet Finder (TPF) were studied through the dynamic MATE lens and shown to address changeability in very different ways. (See Figure 6 below for example tradespaces.) JDAM, as an actual system in use, was shown to be a highly changeable system due to its use of three key path enablers: modularity, commercial off-the shelf (COTS) parts, and simple, excess capacity interfaces. Along with its simple design, these path enablers have allowed the system developers to continuously upgrade and refit the system over time, offering several "accessories" to customize the system to customers, all while maintaining a high level of program success. The JDAM was shown to not only be a changeable system itself, but also a path enabler to flexible and adaptable missions.

TPF, a major space-based astrophysical observatory seeking to characterize extrasolar planets for their potential for life, is aiming for deployment early next decade. The conceptual design phase for this system is ongoing and the architectures under consideration have slowly changed with time, as have the requirements. Since the science aims may change with time, the system itself must be able to change, or have excess capability in order to meet the various demands placed on it. Finding a passively robust TPF architecture may not be possible, as the current set of requirements may not be readily met with a single architecture considered by this study.

The pressure to combine science goals of distinct communities may result in a reduction in the feasible space of design options to a null set. Coupled with detector technological progress, the TPF mission may benefit from waiting before further development as system designers seek to elucidate the key tensions between science goals, available resources, and technical capabilities.

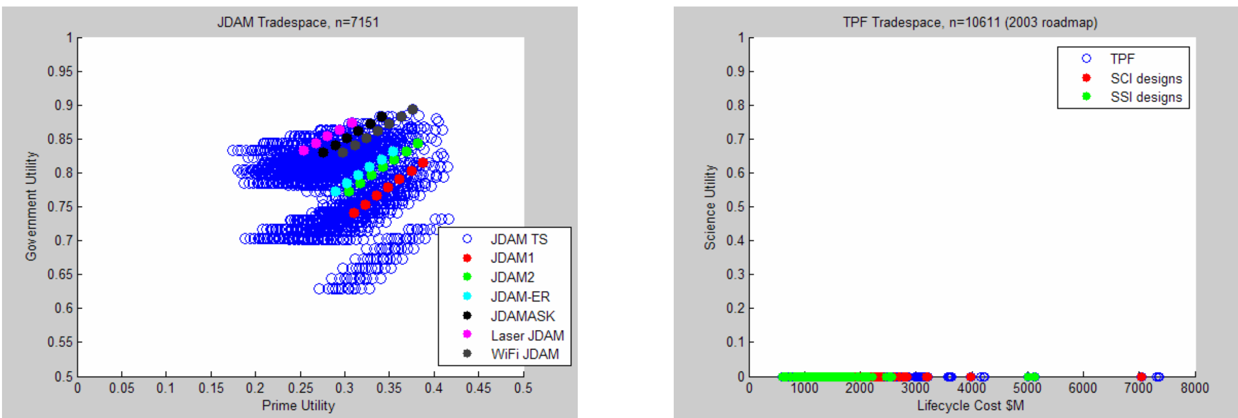

Figure 6 JDAM and TPF tradespaces

Not only can the precursor MATE work each be seen as special cases of the generalized dynamic MATE approach, but also system properties, the "ilities," have been defined within a unifying framework for their consideration during Conceptual Design. It is only when designers have a good grasp of the dynamic flow of value that they can develop truly long-lasting valuable systems. From the mind of the decision maker through a system in its context and back through the eyes of the decision maker, perception of value passes through many phases and transformations. The role of a good designer is not about technical achievement, but about value creation and sustainment.

<u>Staffing</u>: Adam Ross. Committee chair: Professor Daniel Hastings. Committee members: Professor Deborah Nightingale, Professor Olivier de Weck, and Professor Thomas Allen.

<u>Timetable</u>: The research was begun in Spring 2003 and was completed in Spring 2006.

<u>Expected Products</u>: The primary product of this research is a PhD dissertation for the Engineering Systems Division. Other products will include several conference papers (including INCOSE International Symposium 2005 and AIAA Space 2006) and at least two journal papers, as well as indirect influence on several Masters theses and research thrusts in the LAI systems engineering related research clusters.