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

Lauren Viscito[1], Debarati Chattopadhyay[2], Adam M. Ross[3],

[1]Massachusetts Institute of Technology, USA, viscitol@mit.edu
[2]Massachusetts Institute of Technology, USA, debarati@mit.edu
[3]Massachusetts Institute of Technology, USA, adamross@mit.edu

Abstract
Traditionally, the conceptual design phase of a complex system will lock in the majority of the cost and schedule of the system. During this phase, designers may attempt to include flexible aspects in the system to hedge against future uncertainty. Including these flexibility aspects in a design often comes at a cost, however, in the form of dollars, time, or additional mass. These "extra" costs will drive designs away from Pareto efficiency. Pareto optimality in utility-cost space is often used as a standard tool for selecting 'best' designs during tradespace exploration. Optimality is assessed in a static context, where the costs are more apparent than the benefits. A proposed metric to screen for valuably flexible designs in tradespace exploration is proposed after examining high Pareto Trace coupled with high Filtered Outdegree designs. In order to demonstrate the proposed metric, a satellite radar space system tradespace is parametrically modeled across changing contexts. Designs that produce high Pareto Trace and Filtered Outdegree are examined. The designs that recur on the Pareto Front across epochs, and can transition to other designs for different epochs score well in the proposed metric, and are valuably flexible. This paper describes the process of creating the metric in order to give readers better intuition about designs identified by the metric.

Keywords: *Tradespace Exploration, Flexibility Metric, Concept Design, Epoch-Era Analysis*

1 Introduction

Flexibility is defined in this paper as the "ability of a system to change with the input of an external agent," [1]. Flexibility is an aspect of the system that will allow it to take advantage of the upside of uncertainty, or opportunity, and mitigate the downside of uncertainty, or risk. Flexibility is a desirable quality in a long-lived system, and that a system that is flexible will deliver more value over it's lifetime than a non-flexible system. These ideas have driven the research in recent years to increase understanding of how flexibility can be incorporated into systems during the conceptual design phase.

Tradespace exploration typically displays information on a static utility-cost basis, and therefore a decision maker can readily perceive the cost of embedding flexibility but perhaps not the benefits. Designers need a way to consider flexibility in system design beyond the additional cost. This paper proposes a new metric, called *Value Weighted Filtered Outdegree* (VWFO), for use within a tradespace exploration method, that will identify valuably flexible designs. Real options or portfolio planning get at the value of flexibility by assigning expected monetary returns, which can mask how much flexibility a system has by rolling up costs and benefits. A better way to consider explicit design trades, VWFO is used to provide a ranking of designs in the the tradespace. As a first step in developing this metric, different subsets of designs from a tradespace are examined, and their flexible aspects are analyzed. As flexible designs are revealed, insights from the analysis are combined to derive the Value Weighted Filtered Outdegree metric.

2 Measuring Flexibility Background

Measuring flexibility of a design is not a new pursuit, however there there are several domains in industry that are increasing awareness of flexible aspects in process design. And while the manufacturing and operations research domains have been looking at flexibility in the manufacturing process for many years [2], unlike the study of engineering systems, their concept of flexibility is very narrowly defined within their particular domain. Due to the intent for broad applicability of concepts and methods across domains, the following sections describe flexibility research in the engineering systems domain.

2.1 Types of Flexibility

According to [3] there are two types of flexibility in engineering systems: process flexibility and product flexibility. The first, process flexibility, refers to the capacity of the design process to incorporate and respond to uncertainty in system requirements or user preferences. Flexibility in the product or system, refers to the system's flexibility in operations, or after the system has been through the design process and is fielded. As long as the tradespace exploration model contains design variables for both process and product, the method described in this paper can handle both types of flexibility.

Some methods, such as real options analysis, attempt to place monetary value on individual aspects of flexibility within a system. This approach, however, does not address the amount of flexibility that a system or process has. In the face of unknown unknowns, it is difficult to assign monetary costs and benefits for conducting real options analysis, so the best that can be done is to follow heuristics from [4] and [5], which say that having more flexibility is good, and will en-

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able the system to continue value delivery in the uncertain future.

Compton [6] looks at a method based on network analysis to determine the relative flexibility of circuit manufacturing. Other methods of assessing flexibility look at the comparison of a baseline system to flexible systems [7]. These methods are not suitable to ranking alternatives, as choosing a baseline is contrary to the tradespace exploration method.

Metrics that quantify flexibility rather than valuing it are more abstract than real options analysis. A relatively straightforward method for measuring flexibility is described by Olewnik [8], who uses the distance between points along the Pareto Front as a proxy for the 'cost' of flexibility.

Rajan [9] looks at consumer products, and analyzes the flexibility of a product based on a platform/ modular approach, wherein the product is deemed flexible if it is able to undergo economical redesign (i.e. has more modular parts). This method is limited to a specific way (platforming) to address increasing flexibility, and therefore is difficult to extend as a tradespace analysis metric.

2.2 Real Options Analysis

Real Options is a method for designing under uncertainty[10]. The flexibility of a system is built in as engineering options that may be exercised at a later date. In this paper, 'change mechanisms' are analogous to the options in real options. However, real options analysis places a monetary value under a specific future uncertainty on both the benefits and costs of the flexible system, thereby undervaluing how much flexibility a system may have by calculating the expected return from the options only under the specified uncertainty.

2.3 Tradespace Exploration as Conceptual Design Method

Tradespace exploration is a conceptual design method that enables designers to examine many different designs on a common basis. Typically, designs are plotted in a utility-cost space, which can reveal trends in the performance attributes and can give designers insights into design trades available[11]. These tradespaces are a static snapshot, reflecting stakeholder preferences on system performance. Systems do not exist in a context vacuum, however, and as the context changes, the stakeholder preferences may change, the environment that the system operates in may alter, or both. A period of time with a fixed set of preferences and environment for the tradespace is called an *epoch*. A time-ordered series of epochs is called an *era*[12]. As a designer looks across many different epochs, there are some system designs that may consistently retain high utility, and others that perform poorly in some epochs.

As the dynamic nature of the tradespace exploration becomes more explicit, the 'ilities', or time-dependent performance characteristics of the designs that become relevant when the context changes, become more important. One of these 'ilities' is flexibility. While evaluating the changeability of a design may be accomplished in a static tradespace [13], making judgements about the value of that changeability is subject to the designer's prediction of the future. To identify which designs are valuably flexible requires analysis of how designs can be changed between epochs as well as static system performance.

Tradespace exploration also involves large amounts of data which grows with the number of time periods considered. Analyzing large data sets becomes increasingly difficult given computational constraints. In order to help designers identify the valuably flexible designs in a tradespace, Value Weighted Filtered Outdegree (VWFO) can be used to filter the tradespace for valuably flexible designs. In this paper, VWFO is motivated and computed for two subsets of designs in a tradespace case example, including those that are highly robust and those that are highly changeable.

3 Approach

The approach for the example tradespace case study relies heavily on previous work accomplished in developing Multi-Attribute Tradespace Exploration (MATE) [1], as well as Epoch-Era Analysis [14] and other tools used to analyze tradespace results. This section presents the generalized method followed in this paper. The follow section presents the method in the context of a case study.

3.1 Stakeholder Value Elicitation

The first and most important step in MATE is eliciting the stakeholder's value propositions [15]. Typically, this is accomplished by interviews with the stakeholder, where the interviewer asks for concept independent attributes. This allows the stakeholder to divorce the technical concepts and constraints from needs or desires. Attributes are how the system is assessed: if the system meets or exceeds the attribute levels, then the stakeholder should be satisfied with the design. Attributes have a corresponding assigned utility, which is ultimately used to rank the trades available to the designer, and is used extensively in later analysis as a basis for comparing the "goodness" of alternatives to decision makers.

3.2 Model the System

The designer, or team of designers, create a parametric model of the system concept under consideration. Design variables, or those aspects of the system that the designer can control, are selected based on the first or second order impacts in driving the stakeholder's attributes. These design variables are fed into the computer model, and the systems' performance in the stakeholder attributes is assessed.

The model needs to be detailed enough that change in the design variables is captured in the performance results. Trades among the design variables become clear as the performance trends are revealed[15].

Attribute	Description
Resolution	The minimum separation between targets that permits them to be distinguished
Field of View	The area of the earth that the Radar has access to within its normal range of motion
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
Revisit Gap Time	The number of observations (i.e., passes) of a given target over the course of a single day
Min Discernable Velocity	Minimal velocity at which a target can be distinguished from the background
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
Self Geolocation Accuracy	The system's reported location of an image on the surface
Number of Target Boxes	The number of target boxes that can be imaged by a single satellite during a single pass
Number of Targets Per Pass	The number of targets the Radar can image within a given target box for a single pass
Tracking Latency	Time between the imaging of a target and when the full image is downloaded to the ground
Imaging Latency	Time between the imaging of a target and when the full image is downloaded to the ground
Track Life	Length of time that a single target can be tracked (continually imaged)

Table 1 – *Attributes for Satellite Radar System Case Study*

3.3 Epoch-Era Analysis

Epoch-Era Analysis [12] is one method of modeling the system lifetime. A tradespace is evaluated in a unique context, defined as a period of time with fixed stakeholder preferences and the environmental conditions, called an epoch. Several epochs are strung together in a scenario to form an era. The system is then modeled under many different epochs. As the number of epochs modeled increases, the amount of information available to the designer also grows.

3.4 Pareto Tracing

A Pareto Efficient set of designs, or those designs that are non-dominated, can be determined from the utility-cost plot for each epoch. A Pareto Efficient design has the highest utility of all other designs at a given cost, and represents the best "value" designs. The Pareto Trace of a design is the "number of Pareto Sets containing that design", [16]. Designs that have very high Pareto Trace are said to be value robust. These designs have the ability to maintain high utility over changing epochs. After all epochs are evaluated, the Pareto Trace for each design is normalized by the number of epochs evaluated. This is called Normalized Pareto Trace or NPT.

3.5 Filtered Outdegree

Previous work[13] has assessed changeability in tradespaces through calculating the number of possible transitions to alternate design configurations a given design can make within the tradespace. When viewed as a tradespace network, this is called the 'outdegree' of a design. Only counting the transitions available at an acceptable cost results in 'filtered outdegree' or FOD. Since this represents the number of acceptable changes that a design can make, it is a measure of the changeability of the design.

3.6 Selection of High NPT and FOD Designs

Tradespace exploration may result in hundreds or thousands of designs, and Epoch-Era Analysis generates a unique tradespace for each epoch. After analyzing the general trends of the tradespace, a designer may wish to identify which designs are valuably flexible. It is proposed that looking at highly value robust and highly changeable designs will reveal designs that are valuably flexible. Several designs from an example tradespace data set are selected based on NPT or FOD, as a beginning point for analysis.

3.7 Era Spider Plot

In order to see if the value robust and highly changeable designs selected in the section above will give a designer insights into valuably flexible designs, the designs are placed on a spider plot for further analysis. A specific era is selected for analysis by the designer during Epoch-Era Analysis. This era may consist of any number of epochs, however in example tradespace in this paper, the length of the era was limited to twenty years, and the number of epochs is five or less. Once the subset of designs is selected (in this case, those designs with high NPT or FOD), they are placed on a era spider plot. This spider plot depicts the epochs in the era in time order. The radials of the plot are utility axes, and the designs are placed on this axis. The stringers (lines between design points) between designs are the allowable paths showing transitions from one design configuration into different configurations. Preliminary results indicate that the plot becomes too dense for interpretation when the number of designs exceeds twenty. The designer then uses the era spider plot to delve deeper into the relationship between designs and epoch changes.

3.8 Development of Flexibility Metric

From the information gained by looking at highly changeable or highly value robust designs, a metric is developed that incorporates the possible net utility change of a changeable design, and guidelines for where to look in the design space to find these designs. The metric can be applied to a subset of the design space, as is the case in this paper. In future studies, the metric can be applied to the entire design space. By reusing information that is generated during Epoch-Era Analysis this metric takes advantage of the work already done with previous steps in tradespace exploration.

4 Case Study- Satellite Radar System

The case study used in this paper a monostatic (single aperture) satellite radar surveillance system (SRS)[17]. The para-

Design Variable	Description
Peak Transmit Power	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	The bandwidth of the radar signal. Larger bandwidths generally return better signatures, but have less power spectrum and so require more power
Antenna Area	The size of the AESA array.
Satellite Altitude	The altitude of the satellite in orbit
Constellation Design	The Walker configuration that is chosen for the spacecraft
Communications Downlink	Whether the satellite has a communications system able to use a dedicated communications backbone, such as TDRSS
Tactical Downlink	Whether the satellite is designed with a high power, localized downlink for tactical users
Maneuver Package	The total amount of maneuvering fuel on-board the satellite
Constellation Option	What real option is built into the supply chain

Table 2 – *Design Variables for Satellite Radar System Case Study*

metric model of the system was designed with path enablers, such that when transition rules and analysis were applied to the system, some designs were more changeable than others. The model was run for 23,328 designs, over 245 epochs. These epochs represent the changing contexts, and possible futures. The transition rules are the ways that the user or stakeholder may actively change in the system.

4.1 Stakeholder Value Elicitation

Stakeholder elicitation is captured by interviewing the stakeholder and creating attributes. These attributes must be quantifiable and perceived independent, as required by Multi-Attribute Utility Theory, typically used in MATE to aggregate the system utility. The SRS study has 12 attributes, shown in Table 1 [17]. The attributes are across two different mission areas, imaging and tracking, and have two stakeholders corresponding to the missions. The aggregation method, Multi-Attribute Utility Theory [18], is only technically valid per stakeholder, so the two missions were combined into a higher order "total utility" by an assumed strategic decision maker that internally trades off the importance of these missions. (The study varied the strategic decision maker preferences in order to understand the impact of changing preferences at the strategic level.)

4.2 Computer Model

The attributes tell the designer what the stakeholder in the problem is interested in. The designer then takes the attributes and chooses aspects of the design that can be altered, and will drive those attributes. The design variables chosen for this problem are shown in Table 2[17]. Attributes were assessed for each design in the design space, and a utility and cost was estimated for each design. In this study, the design variables were evaluated at discrete levels. Due to the computation time required to complete a tradespace simulation, the model was run for 23,328 designs. This took several days of computing time, and balanced the competing desires of a detailed tradespace and time constraints.

4.3 Epoch-Era Analysis

The epochs were defined using several epoch variables[14]. These variables describe the context, both the environment in which the system operates, as well as the stakeholder preferences. Like the computer design model, the future scenarios were modeled as discrete variables, and the number of epochs was, in this case, less than the number of possible combinations of these variables. Again, this was limited by time constraints, as well as memory constraints. Analyzing a rapidly growing data set posed an additional computational challenge. The metric proposed in this paper will somewhat alleviate this problem.

4.4 High Pareto Trace Designs

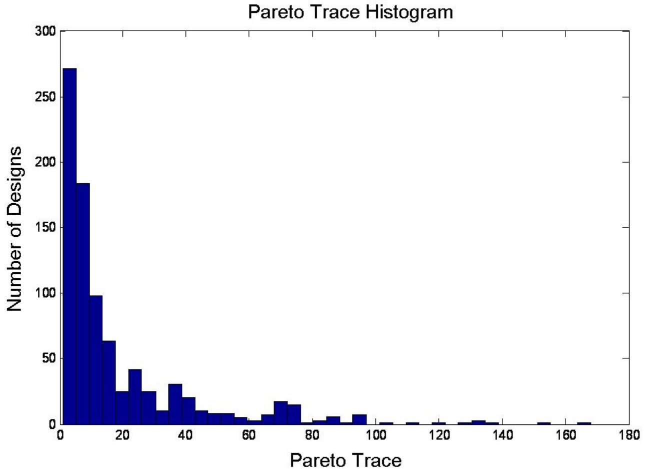

Figure 1 – *Histogram of Pareto Trace for 245 Epochs*

The Pareto Trace of a design indicates how passively value robust that design is[1, 13, 16]. *Passively value robust* describes a design that, without changing, retains high stakeholder utility over many contexts. Figure 1 is a histogram that shows that there are many designs that appear in a few Pareto Sets. Those designs which have high Normalized Pareto Trace are found in Table 3.

In this case study, the Pareto set includes the designs that are highest in total utility for a given cost. Pareto Trace for the design is normalized against the total number of epochs. Therefore, the Normalized Pareto Trace (NPT) is a number from zero to one, with one indicating designs in all epoch Pareto sets, and zero indicating a design that never appears

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 3 – *Utility for High Normalized Pareto Trace Designs*

on the Pareto Front of the epochs that have been sampled.

The distribution of the Pareto Trace seen in Figure 1 follows a general lognormal distribution with an exaggerated tail. The designs under this long tail can be called passively value robust, however the cutoff for this label is a qualitative assessment. A first look at this set of data reveals that there is one design with the highest Pareto Trace: design number 3435, with an NPT of 0.69. Designs with NPT greater than 0.5 were chosen for further analysis. These six designs are shown in Table 3.

4.5 Filtered Outdegree

Filtered Outdegree (FOD) is a metric that identifies changeable designs. Unlike Pareto Trace, Filtered Outdegree does not depend on the utility of the system. Transition rules are the defined set of change mechanisms. In this paper, we will use a single transition rule, “redesign", which enables the change of a design variable from one enumerated level to another, while incurring an associated transition cost, increasing as the cost of the system increases. In this instance, the costs are captured by money and time, however, some transitions may involve changing the SRS orbit configuration, and these rules often impose a fuel cost as well. FOD measures the number of designs that a particular design may transition to at acceptable cost. However, since FOD in no way implies anything about the utility associated with those paths, it is difficult to say how valuably flexible something is based simply on the number of paths.

The details of how to calculate FOD for this study are as follows. Each design that is calculated in the tradespace has a design vector, a performance vector (attributes with utility), associated constants, calculated intermediate variables (e.g. mass) and an epoch vector. The FOD for each design is calculated for each epoch (i.e., we assume that the context remains the same when calculating costs). In order to be "counted," the performance of a design must meet the minimum utility specification for the epoch.

The basic idea of a transition path is that it represents a possible change from one design to another. For instance, design 3435 has a 40 meter antenna. If the size of the antenna were to be changed to 10 meters instead, that would result in a path between design 3435 and the design that is exactly the same as 3435 except for the antenna size. The path is the arc that is notated between these two design points. All paths for a given design are assumed to be directional to the other design. The destination design may then have an opposite direction path that brings it back to the original design. These two paths or, ‘arcs’, are considered distinct and counted separately.

The existence of an arc indicates that a transition is possible. Once the arc is established, it needs to have a cost and time associated with it. Most transitions are not free, both in the sense of budget and schedule. Changing designs will include a transition and a ‘friction’ cost representing inefficiencies and effort in executing a change, and this will apply even if the design moves from a very expensive design to a less expensive one. Anticipated cost savings do not materialize in full, because of the associated friction cost. The transition cost is the notional cost to the program to change from one design to another. A designer then designates a transition cost, above which he would be unwilling to incur the expense of changing the system design. This threshold is then applied to all transitions, and only those less than the threshold, or ‘filter’ are allowed.

The designs shown in Table 4 were found to have the highest filtered outdegree. These designs, unlike the high Pareto Trace designs described earlier, tend to have many change mechanisms built into them, such as excess fuel, and the construction of spare satellites. For instance, the maneuver package, which determines the amount of fuel on board the spacecraft, is at the highest or next to highest level for all the identified designs, which would be considered an extra "cost" with no benefit as seen by NPT designs..

4.6 Era Spider Plot

One way to look for flexibility is with a spider radar plot. Inspired by the Performance Gap metric introduced by [19], which displayed the performance gap of the system against the desired mission, the spider plot contains information about the performance of the SRS system, as well as the possible transitions.

One era was chosen as the example for the case study [14]. The era describes a simple scenario, in which the system progresses through changes to the stakeholder preferences and target set requirements. This era has five epochs, four of which are unique. Epoch 63 is the first, then progresses to Epoch 171, which has a different target set. The stakeholder preferences remain the same, while the performance of the

Design Number	FOD Filter is $\$10^7$	Total Utility			
		Epoch 63	Epoch 171	Epoch 193	Epoch 202
1089	188	0.62	0.63	0.49	0.60
1101	359	0.72	0.72	0.55	0.66
8921	488	0.77	0.78	0.65	0.75
9029	278	0.77	0.78	0.81	0.91
16701	437	0.77	0.78	0.65	0.75
16809	263	0.77	0.78	0.81	0.91

Table 4 – *Utility for High Filtered Outdegree Designs*

systems changes slightly. Next in Epoch 193 the same target set exists, but the stakeholder preferences have shifted, causing the utility of the designs to change dramatically. Epoch 202 retains the same stakeholder preferences, but switches the target set. The era concludes with the stakeholder preferences and target set returning to the conditions found in Epoch 171.

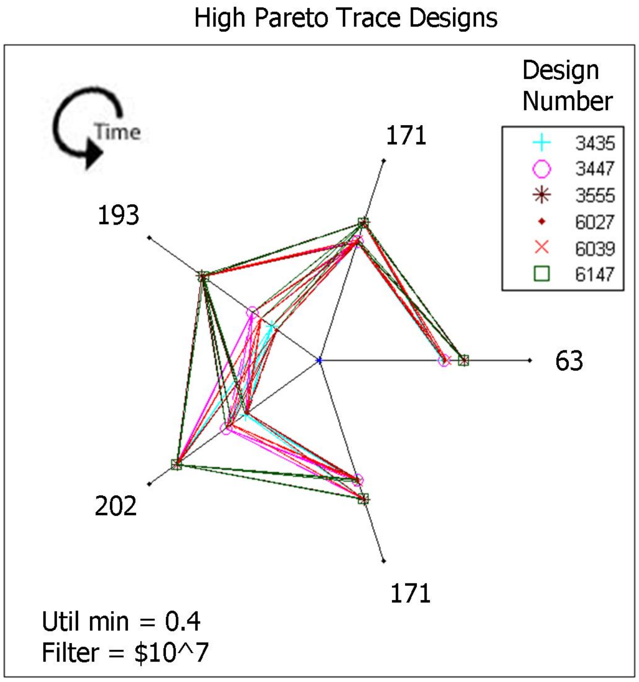

Figure 2 – *Spider plot containing six designs with high Pareto Trace*

In the plot, as seen in Figure 2, the epochs occur sequentially counterclockwise, beginning with Epoch 63. As time progresses, the radials of the spider plot represent a snapshot of each epoch. The ends of the radials indicate a stakeholder utility of one, while the center of the radials is set at 0.4 to clarify plot. The stringers (lines between design points) between epochs represent transition arcs. The presence of a stringer indicates that a transition is possible, at a cost less than a threshold cost filter, which is noted in the lower left corner of Figure 2.

Dashed stringers are used to help distinguish designs that 'stay the same' across consecutive epochs. These are not transition paths, however 'do nothing' is a valid strategic decision for a stakeholder experiencing epoch changes, and should be considered explicitly. These dashed lines can be used to identify the progression of static designs across the era.

The six designs that have high Normalized Pareto Trace (NPT) in Table 3 were evaluated for the several epochs in the era and were then plotted on a spider plot representation as described above. Only transitions to designs in the subset were allowed, this essentially takes a tradespace os 23,328 designs are reduces to a tradespace of six. Figure 2 shows the results for 'redesign' transition rule in the design phase with a cost threshold filter of 10^8 dollars. This filter represents an acceptable threshold for a transition cost less than the cost of the system.

When the high NPT designs are plotted, they all have similar utility. The highest utility design, 6147, has a transition available to design 3555 in the next epoch, where that design is also high utility. The context change from epoch 171 to 193 is more significant. In epoch 193, some designs drop utility significantly compared to others. For instance, design 6027 has the lowest utility in Epoch 193, but is not the lowest in Epoch 171. There are a few transitions from lower utility designs to the higher utility designs. The designs that have change mechanisms available, and do not continue to provide value are not robust or valuably flexible. Other designs are able to recover from utility loss, and transition to a higher utility design in the next epoch. Design 3447, which has lower utility in Epoch 193, has a transition available to design 3555, which in Epoch 202 has higher utility than design 3447. In this way, a decision maker can analyze designs and their interactions to determine is there are valuably flexible designs in this subset.

To compare the value robust designs (represented by the high NPT designs), to highly changeable designs (represented by high FOD designs), the second subset of designs is plotted in Figure3. The differences between the two subsets of designs are extremely apparent in this representation. The high NPT designs have higher utility, but much fewer possible transitions. Again, the transitions available are only those within the subset. An interesting aspect of this subset of designs is the lack of reordering in the utility scale. Unlike the high

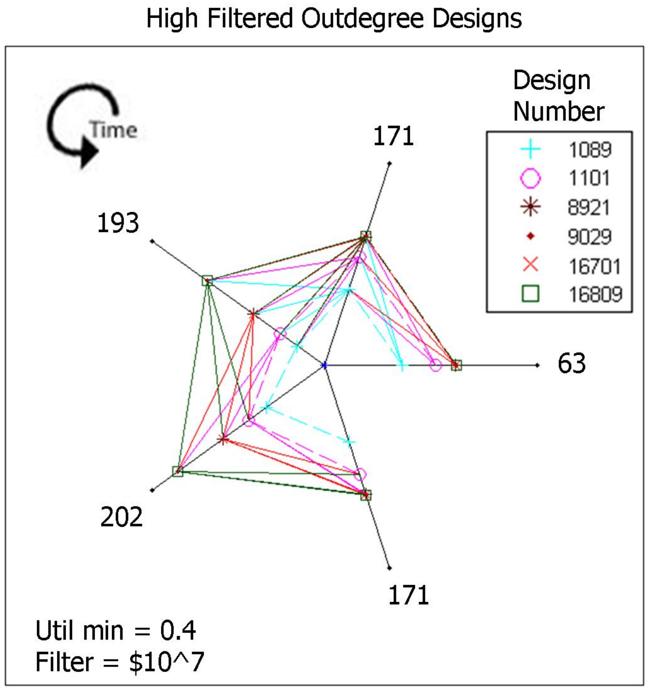

Figure 3 – *Spider plot containing six designs with high Filtered Outdegree*

NPT designs, which tend to be designs up against constraints, the highly changeable designs are not Pareto Optimal, and meet the utility requirements without encroaching on boundaries. This means that as the era progresses, the decision maker may perceive that the best strategy is to choose the highest utility design of the subset and then remain with the same design. Not explicit in this representation is the cost of the designs themselves. These designs, not being Pareto Optimal, are dominated in utility space by less costly designs. However, the designs in this subset are highly connected by transitions, and in the event that the future unfolds in a different era, the value of being able to maintain utility over time becomes apparent, offsetting the apparent cost and "dominance" in the static view.

As a decision makers uses this plot, he can look for trades between having high utility, and having the ability to transition to other designs. The designs that have some useful transitions, and relatively high utility, are the designs that can be considered valuably flexible. From this qualitative approach, we can devise a metric that captures the same process. We call this *Value Weighted Filtered Outdegree*. This proposed metric can be calculated for the subset of designs described here as shown in Equation 1.

$$VWFO_i^k = \frac{1}{N}\sum_{j=1}^{N}[(u_j^{k+1} - u_i^{k+1}) * Arc_i^k] \tag{1}$$

where

N is the number of designs considered

k is the current epoch

$k+1$ is the next epoch in the era

i is the design under consideration

j is the design to be transitioned to

u_i^{k+1} is the utility of design i in the $k+1$ epoch

u_j^{k+1} is the utility of the transition design in the $k+1$ epoch

Arc_i^k is the logical value indicating the presence of a transition arc

This metric captures the utility difference in the destination designs, and is dependent on how many transitions are available. This is not an axiomatic use of utility, as it is not a cardinal scale. The intent of the metric is to act as a screening heuristic, and it is left to the decision maker to make a final call on the value of the design.

For the twelve designs in this paper, the VWFO for each is shown in Table 5. Some designs have zero VWFO. There are several reasons this may be the case: the design may have zero transitions available, the transitions available result in zero net utility, or the design may not be available in the $k+1$ epoch. Designs with positive VWFO, like 1098, 1101, 3435 and 3447, have transitions available to higher utility designs in the first epoch change. This may indicate that these designs are valuably flexible. In a previous section, design 3435 was identified as the highest NPT design. This continues to be a design that may be interesting to a decision maker. As the Era progresses, the VWFO for the designs change.

One way a decision maker can use this information is to look at several eras. Designs with high VWFO for several eras would be a good place to start when planning flexible strategies. Additionally, it may be that the designs with high VWFO share the same change mechanisms. This would indicate that this particular change mechanism is exercised frequently, for instance, varying the amount of fuel carried on board the satellite.

Designs with high magnitudes of VWFO are may be more valuably flexible than others. Designs that have positive VWFO are able to transition to destination designs that have higher net utility. Unlike choosing designs based solely on high NPT or high FOD, VWFO can identify designs that are valuable and flexible, and may lead a designer to different areas of the tradespace.

5 Conclusions and Future Work

During tradespace exploration, a decision maker can screen the tradespace for valuably flexible designs using Value Weighted Filtered Outdegree. This metric calls out designs that are both highly changeable and valuable to the stakeholder. This metric enhances tradespace exploration as prior tradespace analysis techniques account for the cost of flex-

Design Number	Value Weighted Filtered Outdegree 63 to 171	171 to 193	193 to 202	202 to 171
1089	0.13	0.19	0.00	0.00
1101	0.04	0.13	0.11	0.05
3435	0.01	0.11	0.12	0.02
3447	0.01	0.05	0.06	0.02
3555	-0.04	-0.13	-0.09	-0.03
6027	0.01	0.13	0.12	0.02
6039	0.01	0.08	0.07	0.01
6147	-0.04	-0.13	-0.10	-0.03
8921	-0.01	0.04	0.03	0.00
9029	0.00	-0.13	-0.10	0.00
16701	-0.01	0.04	0.03	0.00
16809	0.00	-0.13	-0.10	0.00

Table 5 – *Value Weighted Filtered Outdegree for Selected Designs*

ibility, but leave out possible benefits. Epoch-Era Analysis allows a decision maker to model the future in a way that enables quantification of the dynamic properties of a system.

5.1 Future Work

The spider plot representation has several limitations, the most important of which is that it can only display a limited number of design points and arcs before the construct become unwieldy. Including all the thousands of valid designs on the plot would quickly overwhelm a human's ability to process the information to discover useful patterns and develop insights into the tradespace. VWFO could be used as a screen for the entire tradespace, instead of only applied to a small subset of designs. Further research is required to determine the best way to extend this analysis to larger data sets.

Another limitation of the spider plot representation is that utility is not a metric with absolute meaning for "distance." It is merely an ordinal metric (i.e., the order of the list matters, but the difference between a design with utility of 1 and 0.75 and 0.75 and 0.5 is not necessarily the same 'distance' to the stakeholder at all). Because of the ordinal property of the utility, the intent of the spider plot representation is not to gauge the absolute goodness based on the distance, but rather on the order of the points on the plot.

Additionally, future research is required to assess VWFO over an entire era, instead of only between two epochs.

5.2 Summary

VWFO has been demonstrated to exhibit favorable properties for screening for valuably flexibly designs in a tradespace, accounting for both the amount of flexibility, as well as the potential benefit and cost of the flexibility. Existing flexibility metrics are not suitable for tradespace exploration, as they are limited in domain and computational scope. Future uncertainty about the system operational requirements and context can cause an inflexible system to become obsolete and deliver less value to a stakeholder. Quantitatively identifying valuably flexible designs in tradespace exploration gives a decision maker more effective tools for designing a system under uncertain futures.

Acknowledgements

Funding for this research was provided through MIT Systems Engineering Advancement Research Initiative (SEAri, http://seari.mit.edu), and the Air Force Office of Scientific Research (AFOSR).

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