AIAA Space 2009
Pasadena, CA, 14-17 September, 2009

# Quantifying Flexibility in Tradespace Exploration: Value Weighted Filtered Outdegree

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**Tradespace exploration as a conceptual design tool provides the ability to examine thousands of system designs. Comparing these designs within the tradespace can reveal performance trends based on design choices. Varying the environment in which the system is evaluated adds another layer of complexity on the analysis. Incorporating time and changing contexts in the conceptual design allows engineers to consider 'ilities', or time-dependent system performance characteristics. Flexibility, the ability to dynamically change the system to mitigate risk or take advantage of opportunity, is difficult to assess within static snapshots of tradespaces. Flexibility is valuable in the presence of future uncertainty, so conceptual analysis should also consider future context changes on the system. A metric to identify valuably flexible designs in a tradespace, Value Weighted Filtered Outdegree, is presented and applied to a satellite radar case application. The metric is able to identify design in the tradespace that would not have been identified with existing tradespace analysis metrics.**

## Nomenclature

| | | |
|---|---|---|
| $A$ | = | amplitude of oscillation |
| $N$ | = | number of designs considered |
| $k$ | = | current epoch |
| $k + 1$ | = | next epoch in the era |
| $i$ | = | design under consideration |
| $j$ | = | destination design |
| $u_i^{k+1}$ | = | utility of design $i$ in the $k + 1$ epoch |
| $u_j^{k+1}$ | = | utility of the destination design $j$ in the $k + 1$ epoch |
| $Arc_{i,j}^k$ | = | Logical value indicating the presence of a transition arc from design $i$ to design $j$ in epoch $k$ |
| $P_r$ | = | Signal power received (W) |
| $P_t$ | = | Signal power transmitted (W) |
| $G$ | = | Antenna gain (dB) |
| $\lambda$ | = | Wavelength of signal (m) |
| $\sigma$ | = | Target cross section m$^2$ |
| $R$ | = | Range to target m |

## I. Introduction

The motivation for having flexibility as a dynamic system property is that it allows for leveraging of emergent opportunities and mitigating risks, thereby enabling the system to respond to changing contexts in order to retain or increase usefulness to system stakeholders over time. Flexibility is the ability for a system-external change agent to instigate a state change on a system under consideration.[1] The ability to be changed is a desirable quality in a long-

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lived system, as a system that operates for decades has a higher chance of encountering context changes than a system that operates for only a few years. A space system that is flexible is more likely to deliver value over these changes in context than a non-flexible system. Increasing system costs and operational lifetimes has driven research in recent years to develop an understanding of how flexibility can be incorporated into systems during the conceptual design phase.[2]

The method for conceptual design discussed in this paper is Multi-Attribute Tradespace Exploration (MATE).[3,4] MATE uses computer models to evaluate the performance of many different designs in utility-cost space. Whereas in traditional analysis decision makers had to choose between point designs in an analysis of alternatives, with tradespace exploration they are able to make choices based on information on hundreds to thousands of designs. The increased amount of information can lead to better decisions by increasing understanding of the relationships between design decisions and system performance, and imparts more knowledge about the design problem, but representing dynamic properties such as flexibility in a tradespace requires new metrics.[5] While methods for a static tradespace analysis of the system are well established, analyzing `ilities', those properties that are time dependent, is more difficult.[5] Some analysis approaches, such as real options analysis, measure the dollar value of flexibility,[6,7] rather than quantifying how much flexibility is present in a design. Other analysis tools for quantifying flexibility are extremely domain specific, such as those for the manufacturing domain and process development,[8] and may not be suitable for assessing aerospace systems, which tend to be the unique outputs of a long development project.

Information that is more difficult to glean from utility-cost tradespace representations are the dynamic properties of a system, such as the `ilities' flexibility and adaptability. One approach that has been developed is Epoch-Era Analysis, which uses the concept of "epoch" to encapsulate a time period of fixed context and expectations.[9] An "era" is a time-ordered series of epochs that represent one possible timeline of unfolding contexts and expectations for a system, allowing for the discrete analysis of system exogenous effects over time. Given the characterization of dynamic system exogenous effects, an additional analysis approach called Tradespace Network Analysis[10], can be used to characterize and quantify a system's ability to change states. In this representation a given design has a number of transition mechanisms that it can follow in order to change states, subject to change cost and schedule constraints. System evolution paths can be formed across a tradespace, capturing the transitions of designs from one state to the next, over time. Each epoch can contain a tradespace with thousands of design points, across which the designs may dynamically change. Due to path dependence, the number of change paths increases exponentially over time and therefore making it more difficult to identify useful changeable designs. A metric developed in the research, Value Weighted Filtered Outdegree (VWFO) is introduced in this paper and applied to a case study in order to help a decision maker analyze tradespace results by identifying valuably flexible designs, which are designs that can change to more useful states across epoch transitions. These designs can then be used for the formation of dynamic system strategy.

## II. Case Application Background

Radio detection and ranging, or radar, is the process of transmitting modulated waveforms using directed antennas to determine the range, velocity, and material composition of a target based on the analysis of variation in the reflected signal. Radars are all-weather active sensors, providing products during times when optical sensors are limited.[11]

Radar was first used for military purposes by the British during World War II as a defense against air raids. Radar provided advanced warning of high flying aircraft. The critical nature of radar led to advances in technology in antennas and electronics. After the war, radar was turned to many diverse purposes including air traffic control, weather monitoring, and road speed control. Radar continues to be used by military services. The line-of-sight limitation of radar, as with most radio wave systems, has driven militaries to deploy radars at higher vantage points.[12]

Previous studies from the 1990's examined moving airborne surveillance missions to orbital platforms, thereby gaining the ultimate high ground.[13,14] Several of these studies found satellite masses to be large and were prohibitively expensive, recommending waiting for technology to mature, driven by commercial pull instead of government push. The advantages of a space-based system have lead to periodic revisiting of the concept. Advantages, beyond gaining the high ground, include access to denied areas of the globe and continuous availability for near real time tasking. Disadvantages of a satellite radar system (SRS) are primarily due to fundamental physics (e.g. power falling rapidly over large distances, need for many receivers for coverage, constrained orbits) linked to technological limitations (e.g. directional precision of high power radar, rapid processing of large amounts of data) leading to high costs. Range to target for an orbital platform will be hundreds of kilometers, while an airborne platform range is an order of magnitude less. The longer range requires the transmitted power to be increased substantially due to returned signal attenuation. The radar range equation, showing the unfavorable relationship between received signal power and range to target, ignoring losses is:

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 * R^4} \tag{1}$$

where
$P_r$ is the signal power received (W)
$P_t$ is the signal power transmitted (W)
$G$ is antenna gain (dB)
$\lambda$ is the wavelength of signal (m)
$\sigma$ is the target cross section ($m^2$)
$R$ is the range (m)

Another disadvantage is the inability of a space-based platform to loiter for long periods of time over targets. The range equation necessitates lower orbit altitudes to combat signal loss. Achieving continuous coverage of a target would require large numbers of satellites. Once in orbit, repairing and upgrading the satellites is near impossible except via software upgrades or launching additional satellites. The inability to change the system reduces the useful lifetime of the system as compared to comparable airborne platforms, leading to overdesign and accompanying large costs for space-based assets. The technology associated with space-based radar platforms is still being developed, and the end result of the technology development is still unknown.[15]

The Satellite Radar System model is described in more detail in Ref. 16. The case study uses the Responsive System Comparison (RSC) processes to guide the tasks in the tradespace exploration activity.

## III. Responsive Systems Comparison

Multi-Attribute Tradespace Exploration (MATE) is a generalizable method that elicits stakeholder preferences and uses them to guide the generation and evaluation of a large number of designs. MATE was developed to bridge the gap between formal engineering requirements and the creative design process as well as to generalize the design process using computer modeling and utility theory.[17]

Responsive Systems Comparison (RSC) methodology was developed to merge a number of emerging analysis approaches into a coherent framework to guide the analysis of a large number of designs in terms of their ability to maintain "dynamic relevance," meaning the ability to continue to deliver benefits at cost to multiple stakeholders over time across changing contexts and expectations.[18] Using the concept of "epoch," a time period with fixed context and expectations, and "era," a time-ordered series of epochs representing a possible dynamic timeline for system-exogenous factors, RSC specifically quantifies context changes, addressing uncertainty that may enter into the design performance and evaluation. RSC contains a set of seven processes that specifically address context changes, requiring more analysis effort than traditional conceptual tradespace exploration, but leading to better problem formulation and framework for the computer modeling effort.

Each process is highly coupled and in some cases iterative (e.g. Design Tradespace Evaluation). Some processes may also be conducted in parallel (e.g. Multi-Epoch Analysis and Era Construction). Other processes must follow in series (e.g. Design Tradespace Evaluation and Multi-Epoch Analysis). Figure 1 shows the dependencies between and among the processes. The metric discussed in this paper, Value Weighted Filtered Outdegree, is intended as an additional metric for analysis of designs during the Multi-Epoch Analysis, Era Construction, and Path Analysis processes, and operationalizes the concept of "valuably flexible" into a usable metric that can be used for screening a large number of designs to select a few for further consideration.

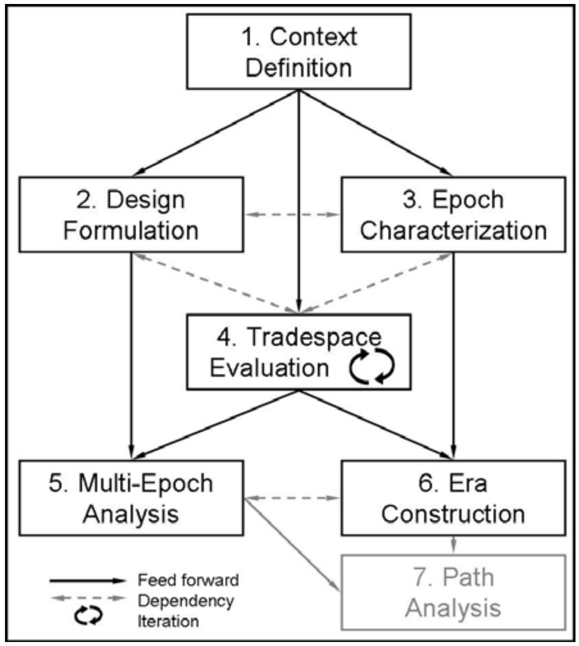


**Figure 1. Responsive Systems Comparison (RSC).**

A detailed description of RSC as applied to the case study can be found in Ref. 19. The following sections describe the epochs and era under consideration in the SRS case application.

### A. Epoch Characterization

The epochs considered for SRS case application were defined using several epoch variables.[20] These variables describe the system-exogenous factors that will affect the perceived success of the system over time including both the context in which the system operates, and the stakeholder preferences. The Epoch Vector (EV) is defined in Table 1. The variables in this table were derived through an iterative process identifying key uncertainties in context and expectations, leading to a set of four categories: policy, resources, infrastructure, and end product use. These categories were then used to derive example epoch variables such as available communication infrastructure, available technology levels, national priorities for missions, availability of complementary airborne assets, and the presence of hostile jamming.. Given the large set of possible contexts, the decision was made to reduce the epoch space by grouping some of the epoch variables together to obtain the initial epoch vector. The enumeration levels of the epoch variables in the vector were also chosen in order to keep the computation time to a level reasonable given the constrained computational resources available for this project. However, the coarse sampling was done in a way that still captured the dynamic properties of the system over many diverse context changes. A full enumeration of the EV results in 648 epochs of which 245 where simulated for this study.

**Table 1. 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, Low |
| Infrastructure | Communications Infrastructure | 2 Levels |
| Systems-of-Systems | Airborne ISR Assets | 3 Levels |
| Environment | Communications Jamming | none, 10 dB |

Each notional target set consisted of two targets, specified by notional country (quantified by latitude) and target radar cross-section (RCS), described as a “scenario” in the table above. For an evaluated epoch, attributes for a design are computed against the worst case of the two targets. In order to reflect possible shifts in mission priorities, when calculating overall utility for a design, the aggregate of the individual mission utilities are weighted in three different ways, indicating the program manager's preference over the two mission areas. Technology level includes radar and bus technology changes, corresponding to high and low TRLs.[15] “Communications Infrastructure" levels indicate the availability of ground stations and space-based relay options. Level one has no relay but can use

AFSCN stations, and level two has WGS and AFSCN stations. AISR levels indicate the availability or non-availability of airborne assets. “Environment" indicates global communications with jamming or without jamming.

### B. Era Construction

Scenario planning was used to construct the eras for the SRS case application. Several epochs were chosen in sequence based on domain expert knowledge. This set of epochs comprises a small number of the calculated epochs, leading to a small set of eras. One era was chosen for demonstration in this case study and is shown in Table 2.[20]

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 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. The progression of these epochs with their corresponding tradespaces is show in Figure 2 below.

**Table 2. 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 | 10 | Conflict resolved, back to pre-conflict environment | Scenario 60, SAR>GMTI, Low tech level, Backbone, No AISR, No jamming |

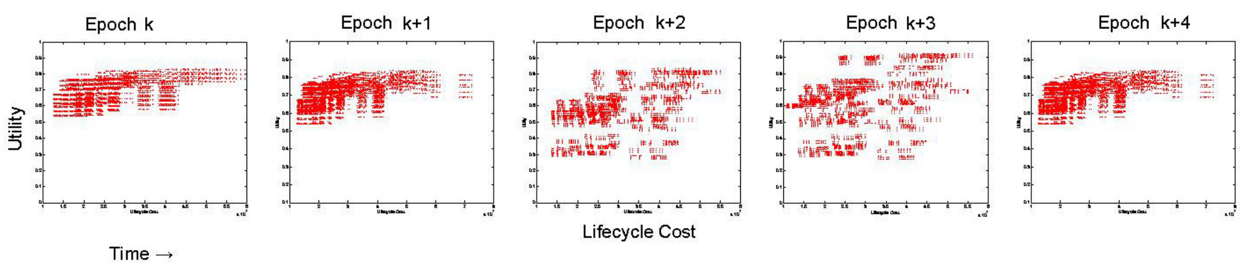


**Figure 2. Tradespace storyboard of Era 1.**

## IV. Value Weighted Filtered Outdegree

Once the era has been identified, VWFO can be applied to the tradespace shifts in the era. The designs that have some useful transitions and relatively high utility are the designs that can be considered valuably flexible. The metric to identify these designs is called *Value Weighted Filtered Outdegree*[21]:

$$VWFO_i^k = \frac{1}{N-1}\sum_{j=1}^{N-1}\left[sign\left(u_j^{k+1} - u_i^{k+1}\right) * Arc_{i,j}^k\right] \quad (2)$$

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

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

$Arc_{i,j}^k$ is the transition matrix with local value indicating an arc from design *i* to design *j* in epoch *k*

VWFO is a metric that captures the utility difference between an originating design and its possible destination designs, is dependent on how many transitions are available, and is defined at the epoch transition boundary between two epochs in an era. Essentially the VWFO of a design *i* within epoch *k* reflects the number of net positive utility change transitions to other designs in the next epoch *k+1*. If one were to ignore the utility change part of the metric, it would become the normalized outdegree of a design within an epoch, representing the fraction of accessible designs in a tradespace (counting the number of arcs between two nodes more than once if more than one mechanism is possible). The intent of the metric is to serve as a screening heuristic, and it is left to the decision maker to synthesize the knowledge into selection of a design for further consideration within a larger acquisition strategy.

**Table 3 Value Weighted Filtered Outdegree for selected designs**

| 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 |
| 16661 | 0.0176 | 0.0188 | 0.0063 | 0.0076 |
| 16701 | 0.0089 | 0.0138 | 0.0043 | 0.0051 |

The VWFO for twelve example designs are shown in Table 3. The designs are specified in terms of their design variables in Table 4 below. The VWFO metric has several features that result in one of three types of values: zero, negative, or positive. There are several reasons for a design to have a zero VWFO: the design may have no transitions available, the transitions available result in zero net utility change, or the design may not be available in the k+1 epoch. Designs with negative VWFO (e.g. 3435, 3447, and 3555) have transitions available, however in net, these lead to lower utility designs across epoch changes. Designs with positive VWFO (e.g. 1089, 1101, 6027 and 6039) have transitions available to higher utility designs in the epoch changes. A positive VWFO is a strong indication that these designs are valuably flexible (i.e. these designs can change and these changes result in utility gains in the next epoch). As the era progresses across the table, the VWFO for the designs change because the assessed utility of each designs changes across the epochs, therefore the utility differences between designs may be different from epoch to epoch.

One way a decision maker can use this information is to look for designs that appear with high VWFO across several eras. It may be the case that designs with high VWFO share similar design features, allowing for the correlation of design features to valuable flexibility. Additionally, one can look at the mechanisms followed when a design transitions across epochs to gain utility. If particular mechanisms appear often, this would suggest further investment in the mechanism may be warranted. For instance, if designs with high positive VWFO often use the "change orbit" change mechanism in order to change to higher utility states, then carrying extra fuel on board the satellite may be a worthwhile investment.[§]

[§] The tentative nature of this assertion is due to the fact that VWFO only relates to the specific epochs investigated. If in reality the system is confronted with unanticipated and/or uninvestigated epochs, then the highlighted change mechanism may or may not enable valuable flexibility.

**Table 4. Design variable values for SRS selected designs**

| Design Number | Orbit Altitude (km) | Walker ID[a] | Antenna Area ($m^2$) | Bandwidth (GHz) | Peak Power (kW) | Comm Arch.[b] | Total Utility |
|---|---|---|---|---|---|---|---|
| 1089 | 800 | 4 | 40 | 0.5 | 1.5 | 0 | 0.6205 |
| 1101 | 800 | 4 | 40 | 0.5 | 10 | 0 | 0.7156 |
| 3435 | 1500 | 3 | 40 | 2.0 | 10 | 1 | 0.7535 |
| 3447 | 1500 | 3 | 40 | 2.0 | 20 | 1 | 0.7580 |
| 3555 | 1500 | 3 | 100 | 2.0 | 20 | 1 | 0.8152 |
| 6027 | 1200 | 3 | 40 | 2.0 | 10 | 1 | 0.7558 |
| 6039 | 1200 | 3 | 40 | 2.0 | 20 | 1 | 0.7642 |
| 6147 | 1200 | 3 | 100 | 2.0 | 20 | 1 | 0.8129 |
| 8921 | 800 | 4 | 40 | 1.0 | 20 | 0 | 0.7703 |
| 16661 | 800 | 4 | 40 | 0.5 | 20 | 0 | 0.7437 |
| 16701 | 800 | 4 | 40 | 1.0 | 20 | 0 | 0.7703 |

[a] Walker ID is a lookup table of characteristics for a Walker constellation, with different possibilities for inclination, number of satellites and the phase (plane orientation).
[b] Comm Architecture 0=direct downlink, 1=able to use relay backbone.

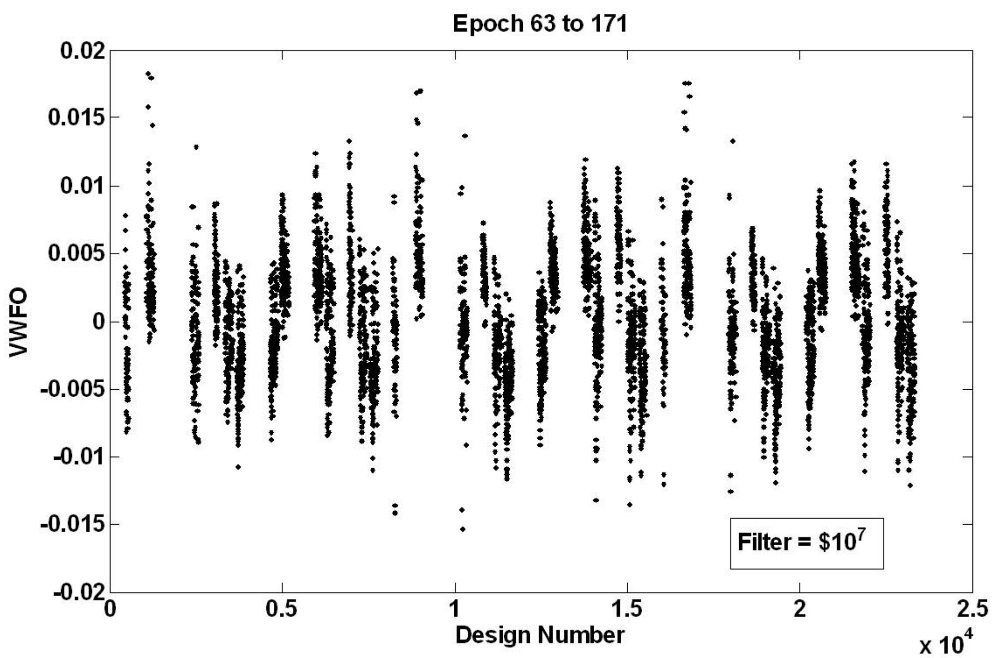


**Figure 3. Value Weighted Filtered Outdegree for Epoch 63 to Epoch 171.**

In order to quickly identify possibly valuably flexible designs, Figure 3 plots the VWFO for an entire tradespace by design number, considering the shift from one epoch (63) to another epoch (171). The striations in the space are caused by the discrete enumeration of the design space. This type of figure can be generated for each epoch transition in the era (e.g. 63 to 171, 171 to 193, 193 to 202, 202 to 171).

Several checks were conducted in order to make sure that the metric was not biased by any unfavorable relationships with other variables. The first check compared the utility of the origin design (design i) against the resulting VWFO for that design, shown in Figure 4. The designs are fairly evenly distributed against the area, and no correlation is seen. The $R^2$ value for the correlation of origin utility to VWFO is -0.0428 with a p value of $5x10^{-4}$, indicating there is no linear correlation between these two. Due to the design space discrete enumeration, the $R^2$ between design number and VWFO (Figure 3) is slightly higher at 0.0143, with a p value of 0.2531. There is still no significant linear correlation, although the slight increase in p reflects the striations noticed in the figure.

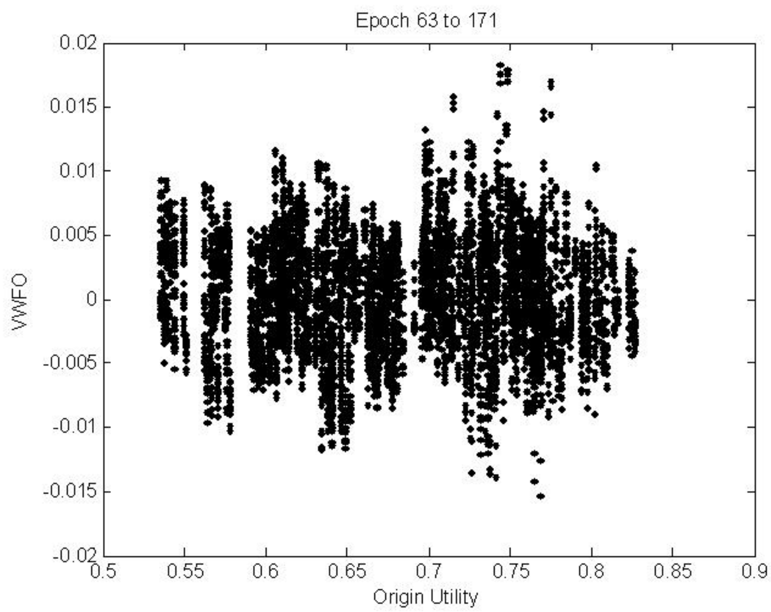


**Figure 4. Total utility of origin design vs. VWFO to check for linear correlation.**

**Table 5. High VWFO design (16661) compared to its baseline equivalent.**

| Design Number | VWFO | Maneuver Level | Constellation Option | Cost difference [%] |
|---|---|---|---|---|
| 1105 | 0.0058 | Baseline fuel | None | -- |
| 16661 | 0.0176 | 2 x baseline fuel | On-orbit spares | 18% |

Design 16661 emerged from the analysis as a design with a high VWFO. Table 5 compares this design to a "baseline" design that is identical, except for its level of path enablers: "maneuver level" and "constellation option," These two variables increase the cost of the design off of the baseline by 18%, but also dramatically increase the VWFO. Inspecting the design and asking whether the extra cost is "worth" incurring depends on whether a decision maker is willing to pay for the increased flexibility of the system. The analysis shows that the 18% premium for design 16661 over design 1105 does not result in extra utility if a design change is not needed, however, it does result in the ability to change to a higher utility design for the epoch changes in era 1. Generalizing this approach can lead to the explicit characterization and trading of design features that enhance valuable changeability (i.e. the "path enablers").

## V. Summary and Limitations of VWFO

Several designs had high VWFO, and one way for a designer to determine which to analyze further is to use Figure 4, which indicates designs with high VWFO and high origin design utility. By having positive VWFO and high starting utility, these designs have more transitions to other high utility designs.

There are several limitations to VWFO. The first is that the results obtained from any study of this nature will depend on the transition rules chosen. If the designers do not specify transition rules that are useful during context changes, no designs will be identified. In addition, it is also dependent on the order of epochs in the era, which determines which designs are valid for transition. Essentially, if a design in invalid in either epoch, it appears as invalid in both. Another problem with the metric occurs when the VWFO of a design is zero. The designer does not know, without further analysis, if that design has zero VWFO because it is an invalid design in one of the epochs, or because the net utility change is zero. The metric is also dependant on the tradespace sampling strategy used by the designer. If the design space has many designs in one area of the design space, which causes the FOD of those designs to increase, it is likely that the VWFO of the design will increase disproportionately as well.

Value Weighted Filtered Outdegree is able to identify valuably flexible SRS designs. The designs identified tend to have some level of design features that enhance changeability but not the highest levels considered, contrary to what might be expected if one were to pursue the heuristic of 'more changeability is more valuable'. However the designer needs to be aware that results may be biased, that is, the lower cost designs may appear to have less expensive transitions if the transition cost is assumed to be a percentage of the initial system cost.

## Acknowledgments

The authors are grateful to the RSC development and satellite radar case study teams for their hard work and dedication. Funding for this work was generously provided by the Air Force Office of Scientific Research (AFOSR) and the Systems Engineering Advancement Research Initiative (seari.mit.edu), a consortium of systems engineering leaders from industry, government, and academia.

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