Demonstration of System of Systems Multi-Attribute Tradespace Exploration on a Multi-Concept Surveillance Architecture

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Abstract
One of the primary challenges for decision makers during concept exploration in engineering system design is selecting designs that are valuable throughout the operational lifetime of the system. The problem is even more difficult when designing Systems of Systems (SoS), which are dynamic, complex, higher-order systems that may be composed of both legacy and new component systems. There are several heuristics and qualitative guidelines for designing SoS in the literature, but there is a lack of practical quantitative methods for SoS concept exploration. Development of quantitative methods for SoS conceptual design will greatly improve the ability of decision makers to select SoS designs that will be value robust over time. These quantitative methods will allow decision makers to consider a larger and more complete set of alternative SoS designs than is possible with qualitative methods alone. A SoS tradespace exploration method is being developed by augmenting the existing Dynamic Multi-Attribute Tradespace Exploration method with SoS-specific considerations, such as the existence of a multi-level stakeholder value function, the incorporation of both legacy and new component systems, and the potential time-varying composition of the SoS. In this paper, a case study of an operationally responsive multi-concept surveillance system for disaster relief is used to illustrate this developing SoS tradespace exploration method. This case study was partially completed as a collaborative project between MIT and the Charles Stark Draper Laboratory, and later extended by MIT. Several surveillance concepts - satellite, aircraft, unmanned air vehicle, and sensor swarms - were considered as possible concept solutions to achieve the surveillance mission objectives. The above system concepts are compared on the same tradespace, demonstrating the ability of the proposed method to allow decision makers to quantitatively compare disparate single system concepts on a common performance and cost basis. Following analysis of the different single system concepts, multi-concept SoS designs composed of heterogeneous components were modeled and then compared with the single system concepts on a common tradespace. This disaster surveillance system case study demonstrates the ability of the SoS tradespace exploration method to enable the quantitative comparison of the relative performance of alternative SoS designs, and thereby contributes to an improved SoS concept design and selection method.

Keywords: Systems of Systems, tradespace exploration, conceptual design, disaster management

1 Introduction

While there are many different definitions and descriptions of Systems of Systems (SoS) suggested in the literature, there is no generally agreed upon definition of SoS. A broad description of SoS is that they are higher order, dynamic systems composed of other independently managed systems.

A common element of all of the literature descriptions is that SoS are systems, and as such have all of the system engineering requirements of traditional systems. However, there are additional considerations that make SoS design more complex than traditional systems. Due to the managerial and operational independence of component systems within an SoS [1], there are both local component system stakeholders and global SoS stakeholders that must be considered during SoS design. As a result of this independence, components may also join or leave the SoS over time, leading to a dynamic SoS composition over the system lifetime. The incorporation of both legacy and new components, and the different levels of control that the SoS designer has over the design and participation of each type of component, introduces additional complexity into the design process. Due to these SoS-specific issues, the critical task in system conceptual design, that of selecting design options that will maintain value throughout the system lifetime, is more complex in the case of SoS than in traditional systems. The added complexity of the aforementioned SoS traits requires new SoS conceptual design methods that utilize and build upon traditional conceptual design tools in order to aid decision makers during this early phase of design.

Quantitative conceptual design methods such as tradespace exploration are often used in design for traditional systems to enable the comparison of a large number of designs and the identification of the tradeoffs between system attributes and stakeholder preferences. However, the SoS literature primarily focuses on heuristics for conceptual design which only allows the comparison of a small number of designs on a very qualitative basis [1, 2]. There is a need for quantitative conceptual design methods for SoS that allow for the comparison of multi-concept disparate SoS designs along with single concept systems on the same performance and cost basis, enabling the designer to explore the full concept design space available. In order to develop such a quantitative method for SoS, the approach in this research, as introduced in [3], has been to extend an existing tradespace exploration method called Multi-Attribute Tradespace Exploration (MATE) through the incorporation of SoS-specific considerations.

The first step in developing a method that allows the comparison of disparate SoS concepts is to identify a method that enables comparison of diverse single system concepts on the same basis. In this paper, for the first time, MATE is applied to a case study to demonstrate the comparison of multiple system concepts on the same tradespace. Multi-concept SoS designs, using the same single system concepts as components, are introduced into the tradespace. The SoS tradespace exploration method enables the comparison of heterogeneous SoS designs on a quantitative basis. The method is also a potential tool for trading stakeholder needs in a multi-stakeholder scenario, an important consideration for SoS which have a large stakeholder set consisting of both component stakeholders and SoS stakeholders. The effect on the system value delivery due to dynamic system lifetime considerations, such as time-varying stakeholder preferences, are analyzed using an epoch-based approach known as Epoch-Era Analysis, leading to the identification of value robust designs.

In this paper, a case study is used to illustrate several key aspects of the tradespace exploration method that are suitable for SoS concept exploration. The ability to compare diverse legacy and new components, as well as SoS, on the same tradespace is the central piece in developing a quantitative SoS tradespace exploration method. The case study presented here demonstrates some of the insights that can be obtained from the application of this method on a practical system design problem.

2 Motivation

Systems of Systems are becoming increasingly important to many organizations that make use of highly networked complex systems that are often independently managed. For instance, the US Department of Defense has increased its focus on SoS design methods employed in acquistion considerations due to the importance of integrating assets across forces to create multi-domain systems [4], such as the Army Future Combat System, or the Air Force Distributed Common Ground Station[5]. Along with defense applications of SoS, there are also many commercial examples of SoS. The National Transportation System is an example from civilian transportation that has been used to illustrate SoS-specific considerations [6]. The simultaneous development of different technologies and vehicles within a space exploration mission can be viewed as a System of Systems problem. Project Constellation currently under development by NASA is regarded as an SoS consisting of multiple ground and space segments [7]. Often, new technologies must be incorporated into an existing set of legacy systems in order to provide additional capability, forming an SoS with both legacy and new component systems.

Due to the independent management of the component systems in a SoS, the design of these systems involves intense decision making in the concept exploration phase in order to select designs that will maintain value over time in a variety of different system contexts. It is well documented in the literature that SoS design is significantly different from traditional system design [1, 2, 8], so new SoS concept exploration methods are needed. While there are several qualitative guidelines and heuristics for SoS conceptual design currently available in the literature [1, 9, 10], such as evolutionary development, architecting at the interfaces, network management and policy triage, there are few well-defined, quantitative methods for SoS conceptual design. A quantitative method of SoS conceptual design will enable the consideration of many more architecture options than is possible through qualitative methods alone, facilitating a more complete exploration of a SoS design space. Tradespace exploration is a method that has been effectively utilized in single system design to identify the tensions between system requirements, allowing decision makers to determine the major trades in performance and cost that are available in the design. A tradespace exploration method suitable for SoS will be a valuable tool for SoS system engineering in the conceptual design phase, similarly allowing the SoS designer to trade SoS performance attributes. The goal of this research is to develop an SoS tradespace exploration method, and this paper introduces an application of this method.

3 Method Description

In developing a rigorous quantitative method for SoS tradespace exploration, the initial step was the characterization of the differences between SoS conceptual design and traditional system conceptual design. In [3], three primary aspects that a SoS conceptual design method must include were identified as :

1. advanced stakeholder analysis due to the presence of both local component stakeholder sets and a global SoS stakeholder set
2. differences in system engineering considerations between legacy and new component systems
3. consideration of the dynamics of SoS composition over time due to changes in system context

In order to develop the prescriptive design method for SoS, these SoS-specific considerations were used to enhance an existing tradespace exploration method known as Multi-Attribute Tradespace Exploration (MATE) [11].

The MATE method allows the decision maker to make trades between stakeholder preferences early in the concept exploration phase by enabling the quantitative comparison of system designs. MATE has been demonstrated as a useful method for single system tradespace exploration during the early conceptual design phase through application to several case studies in the past [12, 13, 14]

In the MATE method, the system performance is measured using stakeholder defined, concept independent system attributes that are obtained through stakeholder interviews. The system designs are functionally modeled and the value delivered by each design to a stakeholder (i.e., the 'utility' of the design as perceived by a stakeholder) can be determined using Multi-Attribute Utility Theory[15]. The multi-attribute utility of each design is plotted versus the derived system cost in a tradespace – a visual tool for the designer to compare designs on the same performance and cost basis. With the help of tradespaces generated by the MATE method, the SoS designer is able to identify the major trades available between system attributes.

To address dynamic changes in context during the system lifetime, an epoch-based analysis approach known as Epoch-Era Analysis has been incorporated into the MATE method[16]. In Epoch-Era Analysis, the system lifetime, or 'era', is subdivided into fixed context, shorter duration 'epochs'. An epoch is characterized by a fixed set of articulated system attributes, constraints, available technology and system concepts. As changes trigger the start of a new epoch, a system may need to transform in order to sustain value, or else it may fail to meet expectations as defined for this new epoch. Using this type of analysis, decision makers can gain insights into how the system will perform when considering possible futures. When many different future contexts or epochs are considered in the analysis, Epoch-Era Analysis provides the system designer with the means to identify passively value robust designs, which are designs that remain high in value delivery to the stakeholder over a variety of context changes. Dynamic MATE and Epoch-Era Analysis, with the incorporation of SoS-specific issues described above, results in a method for SoS tradespace exploration which can aid decision makers during SoS concept design. The primary steps of the SoS tradespace exploration method are shown in Figure 1.

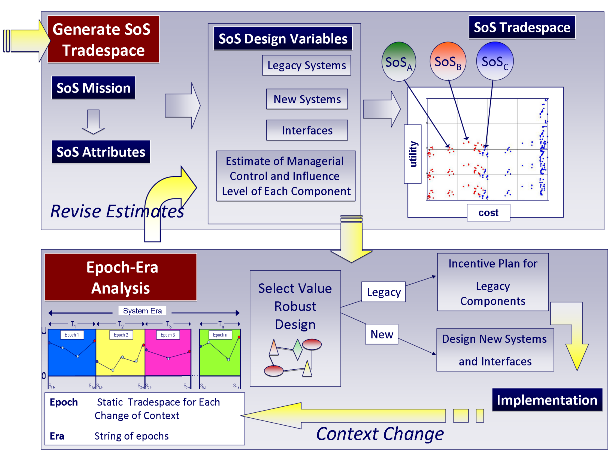


Figure 1 – *SoS Tradespace Exploration Method*

In the SoS tradespace exploration method, the starting point is the definition of the SoS mission, as provided by the SoS stakeholders. The user-defined SoS performance attributes are obtained through interviews of the SoS stakeholders, and are used to measure the value delivery of the SoS designs. At this point in a traditional conceptual design method, potential concepts would be generated and decomposed into their design variables. However, for the SoS, the generation of concepts corresponds to creating a list of potential legacy and new component systems that may be used to accomplish the SoS mission. The SoS 'design variable' set includes these component systems, their method of interaction and interfaces, and an estimate of the 'participation risk' of each component system in the SoS. SoS designs can be generated by combining component systems from the list of possible systems, and the performance and cost for each design can be modeled using the corresponding SoS design variables. Utility can be calculated using a multi-attribute utility function, as in the MATE method[7]. Using this utility function and the model-derived cost, many diverse SoS designs can be represented on a tradespace. This section of the method can be repeated for a variety of future contexts, resulting in a collection of tradespaces representing the system performance in different scenarios, using an analysis method called Epoch-Era Analysis. Tradespace statistics can be generated over a large number of tradespaces thus obtained, and value robust designs can be identified by defining the designs that are provide high value at low cost for many future contexts. Identified value robust designs can be carried on to the next stage of conceptual design, where more detailed analysis and design of new component systems, or interfaces between legacy systems can be conducted. As this method can be quickly repeated, iterations of the method can be done for new changes in context, or when additional detailed information becomes available.

Selected aspects of the SoS tradespace exploration method are demonstrated in this paper through a case study. Firstly, the ability to compare diverse system concepts - such as aircraft and satellite - on the same tradespace is shown. Both legacy and new systems can be compared on a common basis in this manner. Secondly, heterogeneous SoS consisting of multiple single system concepts are compared on same performance and cost basis in a tradespace, alongside single system concepts. Thirdly, the multi-stakeholder problem is approached through the simultaneous consideration of two stakeholders as an example. Fourthly, the analysis of the effects of dynamic context changes including changes in stakeholder preference on the system through Epoch-Era Analysis is used to identify potentially value robust designs. While the full SoS tradespace exploration method is still under development, the demonstration of significant aspects of the method through the case study demonstrates the practical usefulness of the method as a prescriptive tool for decision analysis during early conceptual design.

4 Case Study: Operationally Responsive System for Disaster Surveillance

The case study presented here is an example case done to demonstrate the usefulness of the SoS tradespace exploration method in dealing with multi-stakeholder and multi-concept design problems, and to show that even with minimal resources and functional modeling, this method can provide practical insights to the SoS decision maker. The specific case study selected to fit these objectives was an Operationally Responsive System for Disaster Surveillance, and was conducted by a team of researchers from MIT and the Charles Stark Draper Laboratory. Given the numerous severe natural disasters in the recent past, such as Hurricane Katrina in New Orleans in 2005, the California wildfires of 2007 and 2008, and the Sichuan earthquake in China in 2008, there is a clear need for effective and timely observations of disaster locations in order to aid first responders. For disaster surveillance information to be of use to first-response and disaster relief efforts, it must be provided as soon as possible after unforeseen events in unknown locations. In other words, an operationally responsive system with short response time is necessary to generate disaster observing data that is useful for time-critical disaster relief.

The case study was completed in three phases. Phase I consisted of obtaining the mission description and stakeholder information as well as generating performance attribute and utility information. Phase II consisted of creating a first-pass functional model of several different system concepts and evaluating them on a common tradespace. This phase also contained a basic representation of SoS designs on the same tradespace, demonstrating that this method is capable of being used as a practical tool for SoS concept exploration. The design team used a spiral development model for the project software, and initially produced a first-pass multi-concept model in order to demonstrate the analysis method. Phase III consisted of a second-pass model in which selected concept models were developed in more detail. This phase included the consideration of legacy and new components in the same tradespace, along with SoS designs.

4.1 Phase I: Mission Description and Attributes

The first step in the MATE method is stakeholder analysis. As this case study was undertaken as an example to demonstrate aspects of the method, external stakeholders with defined needs were not available for consultation. The design team generated a list of first responder and system owner type stakeholders that would potentially be users of a disaster surveillance system, provided in Table 1. Then the design team operated as proxies for potential stakeholders and generated stakeholder information through publically available information and narrative role-playing. To establish the mission needs, at first a list of potential disasters that may be within the purview of this mission was generated, and is provided in Table 2.

FEMA	Police
Firefighters	Paramedics
ORS System Owner	Military
Property Owners	Insurance Company

Table 1 – *Potential Stakeholder Set for Operationally Responsive Disaster Surveillance System*

The above list contains short-duration, impulse-type disaster events such as fires and earthquakes, as well as long-duration disaster events such as drought. Many of these disasters would benefit from responsive surveillance data both during the course of the disaster causal event as well as in the aftermath of the disaster. In order to reasonably scope this project, a decision was made to consider only disaster aftermath surveillance, rather than causal event surveillance, i.e. the focus of the mission would be to observe the damage and flooding after Hurricane Katrina, rather than to observe the development of the hurricane itself.

Fires	Riots
Hurricanes	Sickness\epidemic
Thunderstorms\Tornados	Drought
Floods	Traffic Accidents
Earthquakes	Oil Spills
Tsunami	Blizzard
Global warming effects, e.g. breaking ice shelf	Meteor Strike

Table 2 – *Potential disasters to be observed by the Operationally Responsive Disaster Surveillance System*

As there are several short-duration events in the list, two representative events encompassing most of the surveillance requirements for short-duration disaster events were chosen. The selected events for this particular case study were forest fires and hurricanes.

In the absence of specified stakeholders, the design team internally generated a large list of potential stakeholders and probable objectives and goals for each of these stakeholders by proxy, i.e. by investigating and playing the role of each stakeholder in turn and thinking about the needs of that stakeholder.

From this exercise, the primary objective of most of the stakeholders was determined to be ‘reducing and preventing damage to property and people’. This objective decomposed into the following goals for the stakeholders:

- Locate victims
- Locate disaster
- Predict path of disaster
- Locate assets
- Communicate with first-responders

Each of these goals are applicable to an ‘Area of Interest’ (AOI) that is defined by a geographic area on the globe covering the extent of the disaster-affected area, as well as a timeframe of user interest in surveilling that area. The system mission is thus to obtain images of AOI in a ‘timely’ fashion, where the term ‘timely’ is defined by each stakeholder.

The preferences of each of the stakeholders in Table 1 were decomposed further into a set of concept-independent system attributes for each goal listed above, and for each stakeholder. These stakeholder defined attributes were used to measure the performance of the system in the context of each stakeholder's value perception. Associated with each attribute is a name, definition, range of acceptability, and units. Of the large number of stakeholders in the initial list of potential stakeholders generated by the design team, two stakeholders - Firefighter and ORS Owner - were selected as representative for the remainder of the analysis. The combined attribute set for these two stakeholders covered the majority of the total attribute set generated. The attribute sets for the two stakeholders are shown in Table 3.

The performance of systems in the analysis are measured by their performance in these attributes. Single attribute utility curves in MATE represent the preference levels within an acceptable range for each attribute, as defined by a particular stakeholder. In Multi-Attribute Utility Theory, single attribute utility values are combined according to their relative weights into a multi-attribute utility value[11]. The multi- attribute utility function allows aggregation of preferences on single attributes into a single metric of value to each stakeholder.

For the initial first-pass model, the stakeholder utility curves were assumed to be linear between the start and end values of the acceptable range for each attribute. A powerful aspect of the MATE method is the ease of analysis in the case of changes in stakeholder preferences. In Phase II of the analysis, these attribute utility curves and the relative weights of the attributes used to calculate the multi-attribute utilities were varied in order to study the performance of various systems under changing stakeholder preferences.

4.2 Phase II: First-Pass Model

After the attributes were developed and initial utility information obtained in Phase I, the next step in the method was concept generation in which the design team brainstormed design concepts that could potentially fulfill the system requirements.

During the system concept generation phase of the method, several possible system concepts were proposed, of which aircraft, satellite and sensor swarm were chosen for the first pass model due to the availability of information for existing designs within these concepts. These design concepts were then parameterized and modeled to determine their differential performance in the system attributes specified by the stakeholders. The first pass model was primarily composed of look-up tables of performance attributes for several existing designs for each system concept considered.

Using the stakeholder information in the form of attribute utility curves and the relative weights of the attributes, along with information about the Area of Interest, the technical model produced utility and cost values for the Firefighter and ORS Owner for each aircraft, satellite and sensor swarm design. Each design was represented on a tradespace according to the corresponding utility and cost values. Figure 2 shows the model architecture.

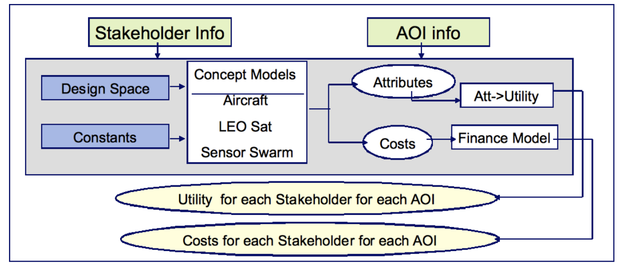


Figure 2 – *First-Pass Model Flow*

For simplicity, the same design vector was chosen for each of the concepts considered in the first-pass model. The four design variables considered were

- Configuration: the type of asset within each concept. 11 existing aircraft, 4 existing satellite, and 2 swarm configurations were considered in the First-Pass model.
- Number of assets: the number of each asset available. Three levels of enumeration for this design variable were used for each concept.
- Wavelength of payload sensor: primary sensing wavelength of the instrument. Two wavelength ranges - visible and infrared - were used for each concept.
- Aperture size of payload sensor: diameter of aperture of the instrument. Three levels of enumeration for this design variable were used for each concept.

With the design variable enumeration considered in the First-Pass Model, a total of 198 aircraft designs, 36 satellite designs and 18 swarm designs were assessed.

The Area of Interest selected for the first pass model was a 100 km^2 area, and the time of interest of the stakeholders in this AOI, i.e. the duration of the mission, was assumed to be three days. Given the stakeholder preferences detailed in Table 3 and AOI information chosen for this mission, the calculated utilities for all the designs can be plotted against each other on traditional utility versus cost tradespaces for each stakeholder. Utility varies from 0 to 1, with 0 representing the minimum acceptable usefulness, and 1 representing the highest stakeholder perceived usefulness. All three different system concept types - satellite, aircraft and sensor swarm - are represented on the same tradespace for each stakeholder. This type of tradespace would enable a designer to compare disparate system concepts quantitatively, as well as identify designs that are high value and low cost for each stakeholder. The set of designs that are the best performance at cost are considered Pareto efficient designs. The Pareto set of designs is generated for each tradespace to obtain the optimal design choices for each stakeholder.

With the utility and cost information available, however, further insights can be obtained from a variety of tradespace plots other than the traditional utility-cost plots. For example, utility-utility tradespaces - such as the one shown in Figure 3 - provide a means to identify trades between the preferences

Attribute	Attribute Description	Attribute Units	Firefighter	ORS Owner
Acquisition Cost	Cost to Acquire System	M	0-800	0-1000
Price/day	Amortized price paid for operations per day	K/day	0-250	N/A
Cost/day	Amortized cost for operations per day	K/day	N/A	0-2500
Time to IOC	Time between initial need or system and initial operating capability	days	0-180	0-180
Responsiveness	Time from request to initial observation of AOI	hours	0-168	0-168
Max Percent AOI Covered	Percentage of AOI imaged by system	percentage	5-100	5-100
Time to Max Coverage	Time to maximum coverage of AOI	minutes	0-1440	0-1440
Time between AOI	Time from AOI1 to AOI2	minutes	0-120	0-120
Imaging Capability	NIIRS[a] level of images	NIIRS level	5-9	5-9
Data Latency	Time between start of imaging to reception of images by user	minutes	0-360	0-360

Table 3 – *Attribute Set for Firefighter and ORS Owner. AOI = area of interest (defined by stakeholder)*

[a]National Imagery Interpretability Rating Scale (NIIRS) is a standardized scale used for rating imagery obtained from imaging systems [17]

of two stakeholders . In this tradespace, the designs that have a high value along both the ORS Owner utility and Firefighter utility axes (the designs in the upper right of the tradespace) are the best common value designs for the two stakeholders. In case of a utility-utility tradespace, the Pareto set of designs for the combined utility-utility-cost objective may not be the same as the Pareto designs for either stakeholder, and thus may include certain compromise designs that are only discovered when considering both stakeholders together in the analysis. This is a powerful tool in identifying system designs that may have been sub-optimal in traditional Pareto analysis, but are very suitable candidates for compromise designs in a multi-stakeholder scenario.

In this tradespace, the designs all appear to have very high utility values. This was due to the attribute ranges and relative weights specified in the stakeholder analysis section. In the first-pass model it initially appears that the stakeholder requested system performance is relatively easily accomplished. In subsequent analysis in this section, the stakeholder preferences are varied to study the variation in utility that results.

Using the generated tradespace exploration data, the Pareto efficient designs, i.e. designs that are the best performance at cost, can be identified. In the first pass model, the lifetime cost was calculated on the basis of an assumed 5 year system lifetime. Two selected Pareto efficient designs for the utility-

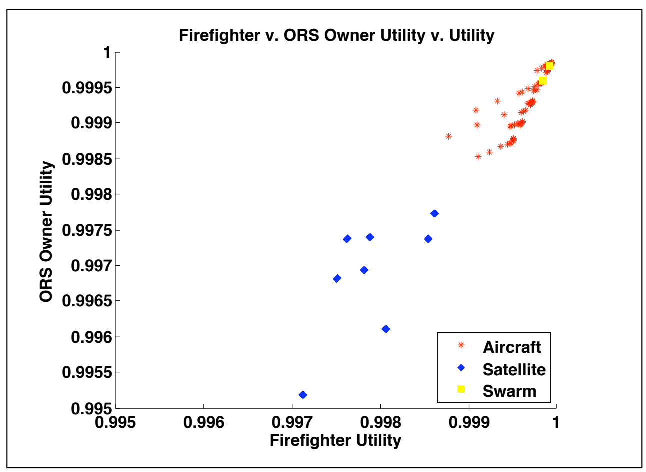


Figure 3 – *Utility-Utility Tradespace for Single Concepts in First Pass Model*

utility-cost objective are listed in Table 4. These designs are optimal for both stakeholders simultaneously at a particular cost.

It should be noted here that utility should not be considered as an absolute number - it is simply used as a means to rank-order the available designs.

Design	Assets	Wavelength	Aperture Size (m)	Firefighter Utility	ORS Owner Utility	Lifetime Cost ($K)
ScanEagle (aircraft)	1	IR	0.04	0.99	0.99	619
Camera Swarm (swarm)	50	IR	0.04	0.99	0.99	76.5

Table 4 – *Two designs belonging to the Firefighter utility - ORS Owner utility -Lifetime Cost Pareto optimal set*

4.3 SoS Modeling

For the MATE method to be applicable to multi-concept Systems of Systems, it must support the comparison of disparate SoS modeling on the same performance-cost basis, as well as allow their comparison to single concept designs. Modeling SoS performance is a complex issue that requires enhanced modeling considerations as described in [18]. For this case study a simple SoS representation was chosen. The assumption was made that the concepts within an SoS design would be operating simultaneously, with the best single concept performance for each attribute being the SoS representative performance. The additional cost required to construct an SoS, in the form of interface construction costs as well as coordination costs between the component systems, is estimated by multiplying the component costs in the SoS by a variable factor. Pairs of concepts from the first-pass design space were combined in this way to generate SoS designs, and their corresponding performance and cost. Figure 4 shows these SoS designs along with the original single concepts, plotted on the same performance-cost basis for the ORS owner stakeholder preference set.

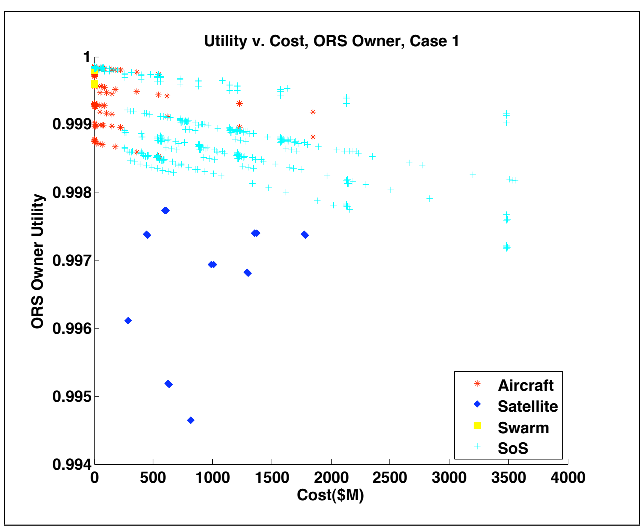


Figure 4 – *ORS Owner Utility v. Cost for Single System Concepts and SoS*

From Figure 4 it is evident that there may be certain SoS concepts - such as a combination of satellite and sensor swarm - that have a higher utility than single concepts, at relatively low additional cost. Quantitative comparison of diverse SoS concepts and single system concepts enables decision makers to draw these types of insights that may be beneficial when there is an interest in utilizing legacy systems to satisfy stakeholder needs. In the early conceptual design phase, when very limited information and resources are available, simplistic modeling such as that presented in the first-pass model can provide interesting insights into the value of creating an SoS versus a single system. However, care must be taken to consider coordination costs as well as hidden and non-monetary costs that may arise in an SoS scenario when looking at such functional models. More detailed system engineering cost models, such as COSOSIMO [19] can be used as further information and resources become available to the design team.

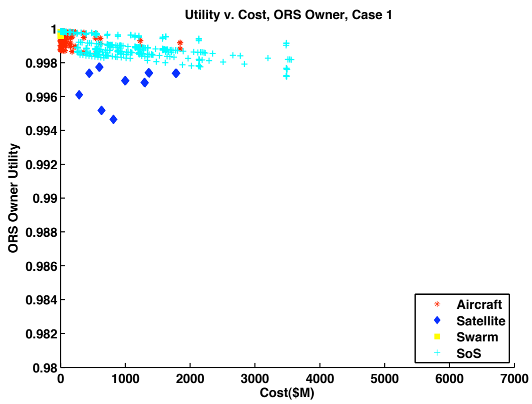
4.4 Epoch-Era Analysis

Epoch-Era Analysis can be coupled with Dynamic MATE which enables the explicit consideration of changing system contexts when determining system value delivery during the concept exploration phase of design. In this method, an 'epoch' is defined as a period of time during which the system context remains static, i.e. stakeholder needs, environmental factors, etc. that affect the system value are unchanged. A change in the system context signals a new epoch. A string of these epochs, called an era, can thus describe a part of the system lifetime. Epoch-Era Analysis allows the designer to consider the effect of many different potential changes in system context on the system value delivery, and thus provides a method to identify designs that deliver value over many changing contexts, i.e. systems that are value robust.

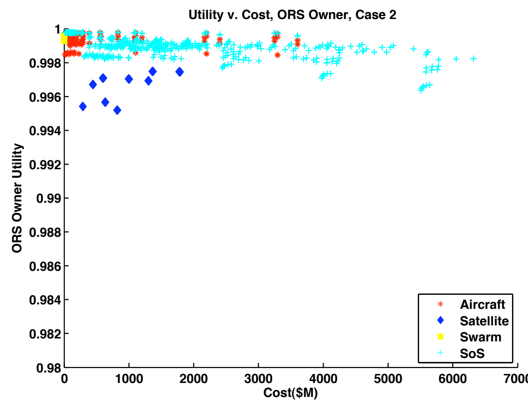
As stakeholder preferences on a system often vary over time, Epoch-Era Analysis can be used to study the sensitivity of the systems in the tradespace to variations in stakeholder preference and is an important consideration in identifying value robust designs.

4.4.1 Change of Stakeholder Preferences

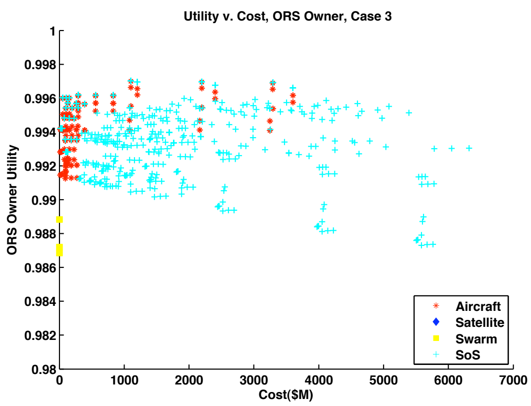
The attribute ranges and the associated stakeholder-provided utility information is likely to change during the system operation lifetime, and even during the design lifetime. Thus it is essential to consider possible stakeholder preference changes during the concept exploration phase. Several different potential preference scenarios were considered in this analysis: a) linear utility curves, b) non-linear utility curves, c) change in relative importance of the attributes to the stakeholders, and d) change in the allowed attribute ranges in performance.



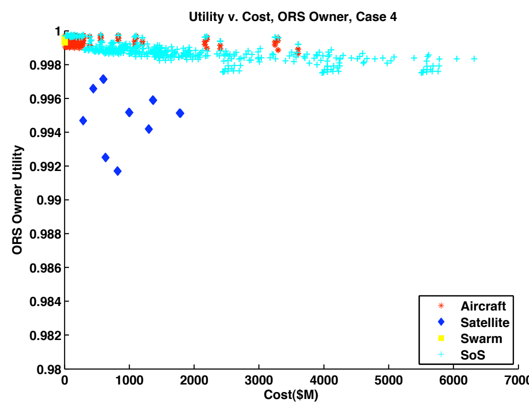
(a) Linear Utility Curves



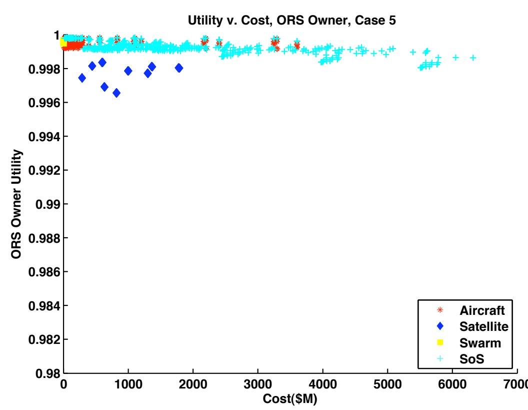
(b) Non-Linear Utility Curves



(c) Change in Attribute Relative Weights



(d) Change in Attribute Ranges, smaller



(e) Change in Attribute Ranges, larger

Figure 5 – *Changes in First-Pass Tradespace with Changing Stakeholder Preferences*

Design	Number of Assets	Wavelength	Aperture Size(m)	Normalized Pareto Trace (N=5)
ScanEagle	1 aircraft	IR	0.04	1
SoS Design (ScanEagle and Camera Swarm)	1 aircraft, 150 swarm units	aircraft=IR, swarm=Vis	aircraft=0.04, swarm=0.01	1
SoS Design (Raven and Camera Swarm)	1 aircraft, 150 swarm units	aircraft=IR, swarm=Vis	aircraft=0.04, swarm=0.01	1

Table 5 – *Passively Value Robust Designs for Changes in ORS Owner Stakeholder Preference*

Each different stakeholder preference scenario is represented by an epoch. Figure 5 shows the changes in the tradespace for the different stakeholder scenarios.

With data from multiple epochs such as the ones detailed above, tradespace statistics can be run in order to identify potential value robust designs. In this case, Pareto Trace can be calculated over the epochs to identify designs that are value robust to changes in stakeholder preference.

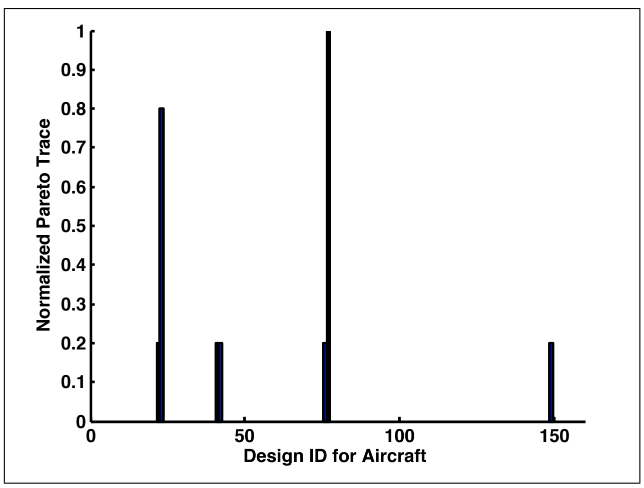


Figure 6 – *Normalized Pareto Trace Values over 5 Epochs for First Pass Aircraft Designs*

The Pareto Trace number for a particular system design is a metric for the passive value robustness of that design in the given epochs [20]. The Pareto Trace number is calculated by determining the Pareto efficient set of designs for each epoch in the test set, and then determining the frequency of occurrence of the designs in the superset constructed of all the Pareto sets. A high relative frequency, i.e. a high Pareto Trace, indicates that a design is value robust over many changes in the system context. A plot such as Figure 6, which shows the Pareto Trace values for the aircraft designs in the First-Pass model, can be used to display the Pareto Trace information for all the designs in a tradespace. In this case, the Pareto Trace is normalized by the number of epochs in the analysis. A list of passively value robust designs can thus be identified using the Pareto Trace metric. Several passively value robust designs generated using this method are shown in Table 5.

4.5 Lessons from First-Pass Model

From the analysis done using the First-Pass model, it is evident that even simplistic models of system concepts can provide valuable insights within the Multi-Attribute Tradespace Exploration framework. The ability to compare multiple disparate system concepts - such as aircraft, sensor swarms and satellites on the same performance and cost basis can provide a decision maker with interesting alternatives that would have been unavailable if concepts were narrowed down too early in the design process. For instance, the decision to consider all three concept types - aircraft, satellite and swarm - throughout the tradespace analysis lead to the identification of low cost options on the Pareto front such as the Camera Swarm option. If the decision had been made early in the conceptual design phase to consider only aircraft options, a potentially desirable design option such as the swarm design might never have been discovered. The tradespace exploration method allows the decision maker to quantitatively compare performance and cost across different concepts over the full system possibility space. Beyond the comparison of single concepts, multi-concept Systems of Systems can also be compared on the same tradespace. The quantitative comparison of SoS options with single system options on the same basis allows the decision maker to make informed decisions about the the benefits and costs associated with creation of an SoS. From this comparison, it can be seen that combinations of some low-cost existing concepts may provide the same or better functionality as a completely new single system design, and thus may meet the mission needs at lower cost. However, when considering SoS 'costs' it is important to consider all coordination costs as well as hidden/non-monetary costs carefully in the modeling effort, to ensure accurate comparisons.

5 Phase III: Second-Pass Model

Once the preliminary analysis using the first-pass model's legacy systems was done, the incorporation of new, clean sheet designs was considered in the form of a second-pass model. In this modeling effort, functional models of two of the system concepts - aircraft and satellites - were developed in order to generate the performance and cost characteristics

AOI Number	Description	Latitude Range	Longitude Range	Time (hours)
1	Hurricane Katrina disaster area, LA	29 ° 50’ – 30 ° 05’	89 ° 50’ – 90 ° 15’	0 –12
2	Witch Creek Fire, CA	32 ° 55’ – 33 ° 22’	116 ° 41’ – 116 ° 59’	0 – 20
3	Cyclone Nargis disaster, Yangon, Myanmar	16 ° 40’ – 18 ° 00 ’	95° 50’ – 97 ° 10’	0 – 12

Table 6 – *Area of Interest Descriptions for Epoch-Era Analysis in Second-Pass Model*

for a space of new designs. In a real life design scenario, the designer would ideally consider both legacy and new systems as options in the design space. The second pass model thus incorporated both types of systems - some existing systems within the aircraft concept, as considered in the First-Pass model, as well as a design space of newly designed aircraft and satellite design options.

The structure of the model was similar to that of the First-Pass model, shown in Figure 2. Both the satellite and aircraft models were parametric models that provided estimates of performance and costs based on technical relationships to obtain attributes from the design vector. The generation of new designs through a full factorial enumeration of the design variables provided a means for exploring parts of the tradespace unavailable to the legacy components used in the First-Pass model.

5.1 Epoch-Era Analysis: Change of Disaster Location

A change in the location of the area of interest may occur during the system lifetime. In the case of this disaster surveillance system, it is expected that the system will need to observe a large number of different types of disasters on different locations on the globe during its operational lifetime. Three different scenarios were considered in this analysis a) a hurricane disaster area, modeled on the Hurricane Katrina disaster area, b) a forest fire disaster, based on the Witch Creek Fire in California, and c) a cyclone disaster area, associated with the Myanmar cyclone in 2007. A description of each of the areas of interest considered is shown in Table 6.

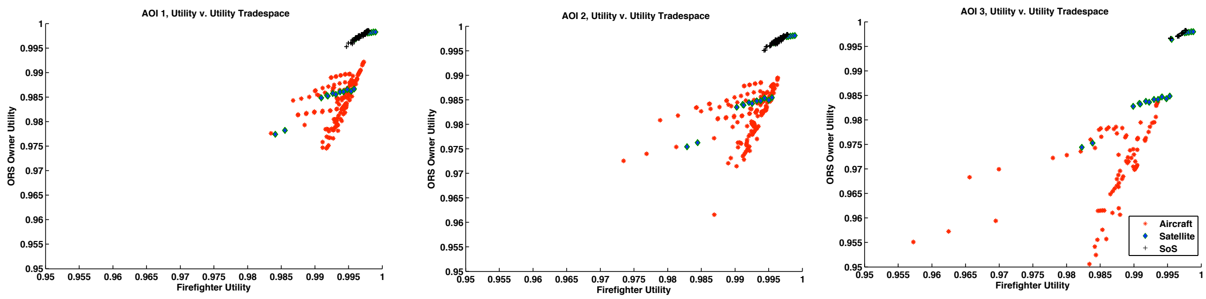
From Figure 7, it is evident that the tradespace changes significantly with the change in epoch, in this case represented by the change in AOI location. The utility of each point design varies with context, leading to not only the change in position of the point in the tradespace, but also in this case, a change in the set of valid designs (i.e., designs within the attribute ranges specified by the stakeholders) between tradespaces.

The set of Pareto efficient designs that provide high value to both stakeholders can be obtained for each of the three AOI considered. It may be possible to find designs that are within the Pareto set for all of the AOIs. Other designs may perform well in one AOI, but not in others. Some sample designs from the Pareto sets for the selected AOI are shown below in Table 7, to illustrate this point. These designs are Pareto efficient for the utility-utility-cost objective. It is of note that the financing method considered in computing the SoS cost is based on an assumed fractional ownership of the system by the SoS designer, whereas the costs for the aircraft and satellite options are assumed to be fully paid by the decision maker. The first three designs listed in Table 7 are designs that are high performance in all three selected AOI, while the fourth is a valid option if the system were only used for the continental US.

From Table 7, it is evident that the SoS tradespace exploration method enables the consideration of a diversity of concepts on the same basis, allowing the designer to consider many different Pareto efficient options that would have been unavailable if conceptual design had been conducted based on a single concept.

6 Conclusion

This case demonstrates the effectiveness of Dynamic Multi-Attribute Tradespace Exploration as a tool for conceptual design of Systems of Systems. The comparison of several different single system concepts, such as satellites, aircraft and sensor swarms has been demonstrated in both the First-Pass and Second Pass models presented in this paper. Quantitative comparison of diverse SoS designs is made possible using this method, enabling decision makers to rigorously compare many more SoS designs than is possible using qualitative design methods. Using Epoch-Era Analysis, the effects on system value delivery due to a variety of system context changes can be studied. In this case study, Epoch-Era Analysis is used to identify potential value robust designs that maintain usefulness over several possible changes in stakeholder preferences and disaster area of interest locations. The Pareto Trace statistic is then used to find designs that are value robust over a variety of different change scenarios. The value robust designs thus identified can be analyzed in depth with more detailed models. This method enables the system designer starting with a large design space to consider many possible options with a relatively small amount of modeling and analysis effort, and then identify a smaller set of value robust designs suitable for further detailed study. The quantitative comparison leading to the selection of options for detailed design is in contrast to the simple narrowing of the concept design space early as is sometimes done in traditional systems design. As a result, more value robust designs can be identified with the new SoS tradespace exploration



(a) Katrina Disaster (b) Witch Creek Fire (c) Myanmar Cyclone

Figure 7 – *Epoch-Era Analysis with Varying AOI Locations*

Design Num	Concept	Description	Lifetime Cost ($M)	Normalized Pareto Trace (N=3)	Pareto Efficient For		
					Katrina Disaster	Witch Creek Fire	Myanmar Cyclone
2116	Aircraft	existing ScanEagle	0.7	1.00	Yes	Yes	Yes
2764	Satellite	120 km, sun-synch orbit, IR payload	12.4	1.00	Yes	Yes	Yes
925	SoS	aircraft (small UAV w/ piston) + satellite (800 km, sun-synch orbit, IR payload)	3.862	1.00	Yes	Yes	Yes
1061	SoS	aircraft (existing Cessna 206) + satellite (120 km, 23 deg inclination orbit, IR payload)	3.22	0.67	Yes	Yes	No

Table 7 – *Selected Pareto Designs for Three Epochs with Change in AOI*

method, than with qualitative methods or traditional concept exploration methods alone. While the case used for this study was a hypothetical one, the insights obtained through analysis using this method clearly show that the method can provide valuable information to decision makers who are trying to select value robust designs early in the conceptual design phase. The spiral modeling method used in the case study, starting with a simple first-pass model and then developing a more detailed second-pass model, demonstrates that this method can be useful at all levels of modeling detail.

The utility-utility tradespaces generated using this method and the 'compromise' set of Pareto designs thus identified can be used to aid negotiations between stakeholders. For instance, in the multi-stakeholder problem that arises in an SoS, where there are local component system stakeholders and global SoS stakeholders, these stakeholders often have conflicting preferences. Utility-utility tradespaces that quantitatively show stakeholders the performance trades to compromise may help the dialog between stakeholders and encourage them to align or change their expectations.

This method is useful for SoS conceptual design, as it enables quantitative comparison of many heterogeneous SoS designs, as well as can aid in stakeholder negotiations. Epoch-Era Analysis can also be repeated rapidly to consider new context changes, introducing the potential for this method to be used after changes in SoS context during the operational lifetime in order to plan value recovery strategies.

7 Future Work

The case study presented in this paper demonstrates key parts of the SoS tradespace exploration method. A case study is currently being conducted that involves the application of the full method that will include further work in methods for combining component system attributes and latent value to obtain SoS performance as well as detailed multi-stakeholder analysis incorporating the important consideration of 'effective managerial control' [3] into the design problem. Fuzzy Pareto Analysis, in which both designs on and 'close to' the Pareto front are consided, will also be used in the Epoch-Era Analysis for SoS [20]. The incorporation of Fuzzy Pareto sets into the Pareto analysis during the identification of value robust SoS designs may provide additional compromise designs that are valuable for multiple stakeholders.

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