Paper #158

A Framework for Tradespace Exploration of Systems of Systems

Debarati Chattopadhyay
Massachusetts Institute of Technology
77 Massachusetts Ave., NE20-343
Cambridge, MA 02139
debarati@mit.edu

Adam M. Ross
adamross@mit.edu

Donna H. Rhodes
rhodes@mit.edu

Abstract

Many qualitative descriptions of Systems of Systems (SoS) exist in the literature, but only heuristics and guiding principles have been suggested with regard to SoS design methods. To assist SoS designers in decision making during conceptual design, prescriptive design methods are required for SoS. To develop a SoS design method, we propose to build on an existing system tradespace exploration methodology by adding SoS-specific design considerations. In this paper, three primary differences between SoS and traditional systems are suggested: stakeholder analysis, dynamics of SoS composition, and the presence of legacy and new components. Additions to the Dynamic Multi-Attribute Tradespace Exploration framework are proposed that will address these differences. The enhanced tradespace exploration method will provide a new approach to SoS tradespace exploration and analysis.

Introduction

One of the primary challenges in engineering system design is making decisions in the concept exploration phase that will result in 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, higher-order systems that may include both legacy as well as newly-designed component, or constituent, systems. Tradespace exploration methods are employed to analyze design spaces in order to aid decision-makers in choosing "good" design alternatives from among a potentially large set during system design. While there are existing methods for tradespace exploration for systems, none have been effectively extended towards SoS tradespace exploration. However, as the emphasis on designing SoS is increasing, there is a need for such a tradespace exploration methodology that will allow designers to make informed design decisions early in the design process, as well as informed operations and management decisions during operation of SoS. In this paper, a method is proposed for analyzing tradespaces for SoS by extending the Dynamic Multi-Attribute Tradespace Exploration method (Ross 2006) through the addition of SoS-unique design considerations.

SoS Definition. While many descriptions of Systems of Systems have been advanced by various authors (Keating et al. 2003; Maier 1998; Sage et al. 2001), there is currently no commonly accepted definition. (Shah et al. 2007) identifies the following three characteristics that are common among many of the SoS definitions in the literature:

1. SoS are systems
2. SoS are composed of other systems that are value producing in their own right
3. SoS constituents have some sense of independence after being assembled into the SoS

While the first two points indicate that Systems of Systems are a class of systems with components that happen to be other systems, the third suggests that SoS engineering may require distinctly different processes than traditional systems engineering. The fact that SoS are themselves systems means that they deliver value to their own stakeholders (global value), in addition to the value delivered by the component systems to their own stakeholders (local value). The 'independence' of component systems in the SoS may require additional system engineering considerations for SoS as compared to traditional systems, whose components do not have similar independence.

Motivation. Over the last decade, interest in Systems of Systems has grown. The US Department of Defense has recently increased its focus on methods of SoS design due to increased emphasis on integrating assets across forces and incorporating new technology to create multi-domain systems (DoD 2006). Multi-modal transportation networks consisting of a variety of systems–such as railways, airlines, roads, etc.–are examples of SoS in the public sector (DeLaurentis 2005). Additionally, many commercial product and service companies are now oriented towards a SoS paradigm through providing integrated solution offerings.

SoS involve more intensive decision making at multiple levels. Unlike traditional systems where tradespace exploration occurs in the early lifecycle phase, in SoS there is a need for a continuous tradespace exploration as component systems enter and leave the SoS. SoS also involve numerous and diverse decision makers. In order to create a shared value proposition, a more formal and rigorous approach to discussing SoS costs and benefits is important.

Currently there is a lack of rigorous systems engineering methods for designing these types of complex, dynamic systems. The goals of this paper are to 1) identify the characteristics of SoS design that distinguish it from traditional system design; 2) illustrate these characteristics using an example SoS; 3) propose enhancements required to extend the Multi-Attribute Tradespace Exploration methodology to the SoS domain to improve SoS trade study analysis and design.

SoS v. Traditional Systems

While several authors have discussed the characteristics of SoS that distinguish them from traditional systems, most of these discussions have been largely qualitative. To develop a generally applicable design method for SoS analysis, these SoS characteristics will need to be quantified. In this section we describe and provide a quantitative basis for the distinctive characteristics of SoS.

Control. SoS are composed of component systems that maintain some level of independence while participating in the SoS. A component system has independent management that makes decisions about the system operation, both when the system is participating in and also when it is outside of the SoS. By virtue of being systems themselves, component systems have their own sets of stakeholders. Some of these local stakeholders may also be part of the global SoS stakeholder set. Figure 1 illustrates this concept of local and global stakeholders.

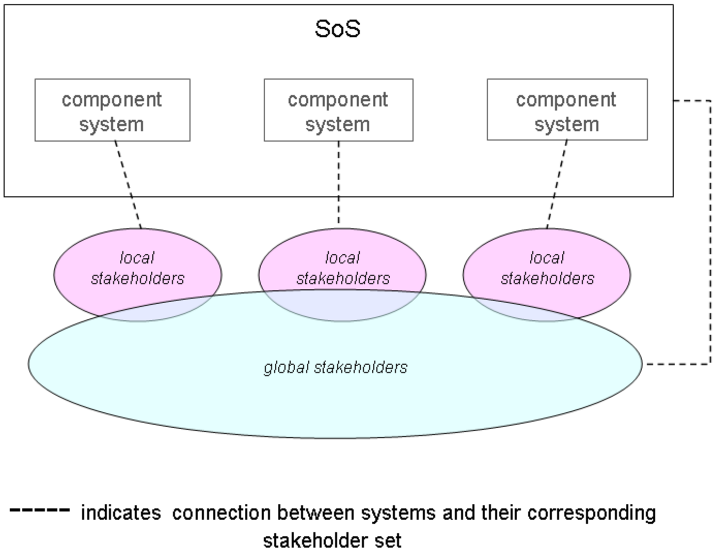

Figure 1: SoS, showing component systems. Component systems have local stakeholders; the SoS has global stakeholders. Some local stakeholders may also be part of the global stakeholder set.

The component system management is required to make two types of system operational decisions: ones that affect delivery of value to local stakeholders, and ones that affect delivery of value to global SoS stakeholders. The component system management decision on whether to participate in the SoS at a given time is one that affects both local and global value of the SoS.

From the SoS designer's perspective, knowledge of the component system behavior determines the design concepts available for the SoS. The SoS designer may have some level of managerial control over the SoS design and operation. (Maier 1998) provides a classification for SoS, based on the level of managerial control available to the SoS designer.

1. Directed: SoS centrally managed
2. Collaborative: SoS not centrally managed, component system participation is voluntary
3. Virtual: SoS not centrally managed, and has no centrally agreed upon purpose

The concept of "degree of control" seems to be implicit in the SoS classification on the basis of managerial control, ranging from no centralized control in virtual SoS to complete centralized control in directed systems. Between the two extremes on the control scale are collaborative SoS, with varying levels of centralized control. Figure 2 illustrates this concept of degree of SoS managerial control.

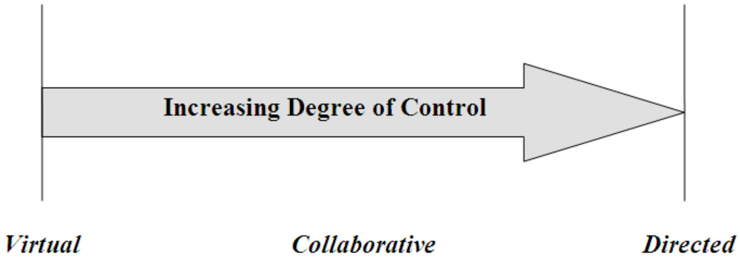

Figure 2: The SoS Managerial 'Control' Scale.

Benefit-Cost Perception. If component system participation in the SoS is optional, as it is in a collaborative or virtual SoS, the component system management determine global level decisions based on their local perception of benefits and costs of participating in the SoS. The component system will consider participation in the SoS only when the local net benefit obtained by the component in the SoS is perceived to be higher than the local net benefit when the component is operating independently.

The perceived net benefit of the system when it is outside the SoS can be represented as the difference between the local benefit and the local cost perceived by the system management.

$$\textit{Perceived Net Benefit } (PNB) = \textit{Local Benefit } (B_L) - \textit{Local Cost } (C_L) \tag{1}$$

The perceived local net benefit of the component system when it participates in the SoS can be defined as follows:

$$\begin{aligned} &\textit{Perceived Net Benefit while in SoS } (PNB^*) = \textit{Local Benefit } (B_L^*) + \\ &\quad \textit{Global Benefit } (B_G) - \textit{Local Cost } (C_L^*) - \textit{Global Cost } (C_G) + \textit{Incentive } (I) \end{aligned} \tag{2}$$

While the component system is in the SoS, benefit at the local level is comprised of value delivered to the local stakeholders from the operation of the component system (B_L^*), plus any additional value delivered locally due to participation of the component in the SoS (B_G). Similarly, cost at the local level is both the cost due to the component operation (C_L^*), as well as any additional costs that may be incurred due to participation in the SoS (C_G). It is important to note that the local value delivery and costs due to the component system operation while in the SoS (B_L^*, C_L^*) may be different from the value delivery and costs when the component system is outside of the SoS (B_L, C_L). A SoS designer may be able to offer incentives (I) to increase the perceived local net benefit. However, the ability of the SoS designer to utilize incentives may be subject to constraints such as laws against side payments or limited resources available to the SoS designer.

For a component system to participate for certain, the perceived local net benefit must be equal to or greater than a threshold for participation. The incentive that will be required to persuade the component to participate is:

$$\textit{Incentive}(I) \geq \textit{Threshold}(Th) - \textit{Benefit}(B_L^* + B_G) + \textit{Cost}(C_L^* + C_G) \tag{3}$$

If the local benefit is sufficiently high, and the cost of both local operation and SoS participation of the component system relatively low, the incentive may be equal to or less than zero in eq (3), and component systems may spontaneously participate without any need for incentives from the SoS designer – this can result in a virtual SoS.

The decision criteria used by the component system management to decide whether or not to participate in the SoS is the relation between the two values of perceived local net benefit – PNB, the perceived net benefit of the component system independent of the SoS, and PNB^*, the perceived net benefit of the component system when it is in the SoS.

There are three possible relationships between PNB and PNB^*.

1. $PNB^* < PNB$: If the local net benefit that the component system obtains when it is part of the SoS is less than the net benefit the component system obtains when operating independently, then *the component system will not join the SoS*.
2. $PNB^* = PNB$: If the local net benefit value is the same when the component system joins the SoS, then *the component system is indifferent about joining the SoS*.
3. $PNB^* > PNB$: If the local net benefit obtained by the component system increases upon joining the SoS, then *the component system may join the SoS*.

Assuming a classical cost-benefit decision rule, it is possible that the component system will choose to join the SoS as soon as there is some amount of net benefit gained due to participation in the SoS. The level of certainty of participation of the component system in the SoS will likely increase with an increase in perceived net benefit, with the component systems definitively participating when the net benefit gained is higher than a particular threshold, which we may call the *threshold for participation*. Thus, the component system will definitively participate when:

$$PNB^* - PNB > Threshold(Th) \tag{4}$$

Assuming a linear relation between the level of certainty of voluntary participation of the components in the SoS and the net benefit gained due to participation, the Certainty of Voluntary Participation can be represented as:

$$Certainty\ of\ Voluntary\ Participation\ (VP) = \begin{cases} 0 & when\ (PNB^* - PNB) \leq 0 \\ \frac{1}{Th}(PNB^* - PNB) & when\ 0 < (PNB^* - PNB) < Th \\ 1 & when\ (PNB^* - PNB) \geq Th \end{cases} \tag{5}$$

The Certainty of Voluntary Participation is a metric that a SoS designer may use to predict the behavior of a component system in the absence of centralized control. However, as many SoS have a significant level of centralized management, it is necessary to develop a measure of the participation likelihood of a component system that combines both the concept of centralized managerial control as well as the probability of participation. This consideration follows.

Control and Influence. As (Maier 1998) suggests, the SoS designer may have varying levels of managerial control over the design and operation of the SoS. In a directed SoS, the SoS designer may have significant control over the component systems in the SoS, but in a collaborative or virtual SoS the designer may need to employ other methods of influence to increase the component net benefit perception above the threshold for participation. Thus, the 'effective managerial authority' that a designer has over SoS component systems is composed of two quantities – 'managerial control' and 'influence'.

To design the SoS effectively, the designer must know the likelihood of participation for each component system in the SoS. Effective managerial authority is correlated with the likelihood of participation – greater effective authority will result in greater likelihood of participation. This is shown in Figure 3.

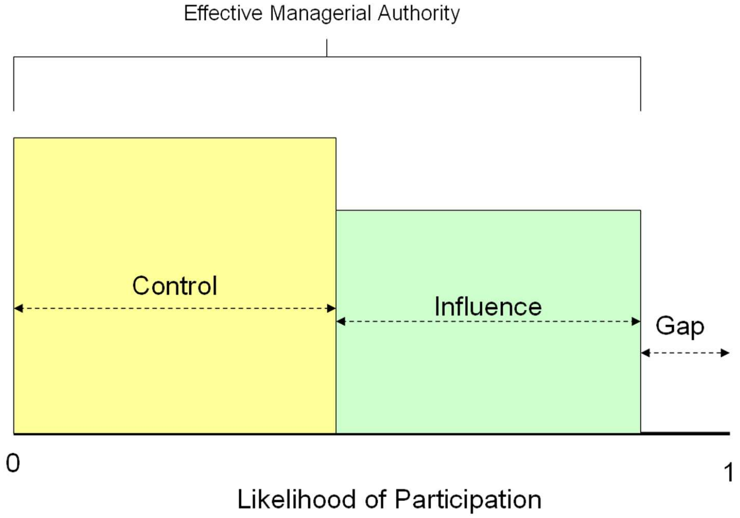

Figure 3: Control and influence, representing likelihood of component system participation in SoS.

Control is the level of direct authority the SoS designer has over a component. A measure of centralized SoS control can be represented as *the percentage of time that a component system is guaranteed to be available when needed by the SoS designer*. Assuming a managerial control scale that is linear from 0 to 1, directed SoS are characterized by a managerial control value of 1 – the component systems will always be available in the SoS component system set when required by the SoS designer; virtual SoS are characterized by a managerial value of 0 – there is no guarantee that the component system will be available for the SoS at any time.

Influence is the ability of the SoS designer to persuade the component system to participate in the SoS, by changing the perceived local net benefit value of the component system. Influence can thus be represented by the certainty of voluntary participation (eq (5)). The combination of control and influence determines the likelihood of participation for a component system in the SoS. When this likelihood is 1, the component system is guaranteed to participate in the SoS. However, the likelihood is usually less than 1, as control and influence may both be constrained by various factors. The difference between certain participation and effective managerial authority – shown as 'Gap' in Figure 3 – represents the risk of a component system not participating in the SoS. When such a gap exists, a designer may need to make contingency plans for dealing with uncertainty in SoS composition.

The participation risk—the risk of non-participation of the component system in the SoS—is:

$$\begin{aligned} \text{Participation Risk} &= 1 - (\text{Effective Managerial Authority}) \\ &= 1 - (\text{Control}\,(MC) + \text{Influence}\,(In)) \qquad \text{when } 0 \le (MC + In) \le 1 \end{aligned} \tag{6}$$

Using eq (5) and eq (6) to relate influence to certainty of voluntary participation (VP), we obtain the following function for participation risk:

$$\text{Participation Risk} = \begin{cases} 0 & \text{when } MC = VP = 0 \\ 1 - (MC + \frac{1}{Th}(PNB^* - PNB)) & \text{when } 0 < (MC + VP) < 1 \\ 1 & \text{when } (MC + VP) > 1 \end{cases} \tag{7}$$

Returning to the SoS managerial control scale defined earlier, the control-influence structure for each of the three cases: directed, collaborative and virtual SoS, is discussed below.

1. Directed: In a fully directed SoS, the designer has complete managerial control over the component systems, i.e. MC=1, and thus participation risk = 0 with no need for influence. This situation may arise in a military SoS, where there is a defined management hierarchy, and component systems are obligated to participate in the SoS if so directed.

2. Collaborative: In a collaborative SoS, MC is between 0 and 1. In this case, in order to persuade a component system to participate, the SoS designer must increase the influence level to reduce the gap between MC and 1. This increase in influence can be accomplished through a) increasing the component perceived benefits, b) decreasing the component perceived costs, c) increasing the incentives offered, or some combination of these options. Transportation systems consisting of airlines, roads and railways are examples of collaborative SoS.

3. Virtual: In a virtual SoS, there is no centralized control, i.e. MC is 0. So influence must be increased to decrease the gap. If the local benefit due to SoS participation is exceptionally high and the local cost low, component systems may self-assemble to create a virtual SoS, without any need for incentives. (Maier 1998) suggests that the World Wide Web is a virtual SoS. Participating systems in the WWW obtain high local benefit from participation in the SoS, while the cost of participation – conforming to certain published standards – is comparatively low. The high benefit and low cost results in a high influence value, which increases the likelihood of participation of components in the SoS despite lack of direct managerial control.

Differences between SoS and Traditional System Engineering

In order to extend single system tradespace exploration methods to the SoS domain, several differences between single system design and SoS design are identified. These differences include more complex stakeholder analysis, the dynamics of SoS composition, and the presence of both legacy and new components.

Stakeholder Analysis. Stakeholder analysis is undertaken by a system designer to identify all the system stakeholders – those who can affect, or will be affected by the system – and to determine the stakeholders' success criteria, which are then used to define the system goals. When there are multiple stakeholders, the system designer must determine how to trade-off between them, as well as the distribution of costs and benefits among them. This 'multi-stakeholder problem' increases in difficulty with the number of stakeholders for a system.

In the case of SoS, both local and global stakeholders must be considered in the stakeholder analysis. The resultant set of stakeholders is therefore larger than that of a component system, making consideration of the preferences of all the stakeholders and resolving conflicting objectives among them difficult. Additionally, the SoS designer needs to account for the allocation of costs and benefits among the stakeholders at two levels – local and global.

To satisfy both local and global stakeholders, the SoS must provide an acceptable level of value at both the local level and the global level. This dual value proposition is a key consideration for SoS design that does not exist in the design of single systems. The SoS has both the SoS level of stakeholders, as well as each component system level stakeholders, who may have conflicting objectives. The multi-level value proposition that results from this distribution of stakeholders is a characteristic feature of SoS, and any successful SoS design methodology must incorporate this concept.

The SoS designer must also consider the potential loss of value delivered to component system stakeholders due to the participation of the component system in the SoS. There may be significant costs involved in integrating the component system into the SoS and constructing interfaces with other components. These costs need to be anticipated and incorporated into the benefit-cost analysis for each component system. According to the control-influence model described earlier, a component system will only participate in a collaborative or virtual SoS if the perceived net benefit is greater than the threshold for participation.

Dynamics of SoS Composition. In the absence of complete centralized control in the SoS, the component systems participate only when the perceived net benefit is above the threshold that satisfies the local stakeholders. If this perceived net benefit changes at any time during the SoS lifetime, the component may join or leave the SoS. Component system availability also depends on development schedules, which may be different for each component system in the SoS. As SoS are often constructed to fulfill time-critical needs, it may be necessary to deploy a partially functional SoS composed of currently available components to provide value as soon as possible. Thus the SoS is dynamically changing over its lifetime. The concept of graceful degradation of value for systems, in which a system continues to provide a reduced level of value during and after system degradation, rather than providing no value at all, is an important consideration for dynamically changing SoS. If the SoS is to maintain a specified level of value delivery during and after component changes, the designer must take the time-varying component system composition of the SoS into account.

Legacy and New Systems. SoS often consist of a combination of legacy and clean-sheet component systems. The SoS designer may have limited control over the design and operational characteristics of legacy systems, and much greater control over new systems. The combination of the constrained design space of the legacy systems and the relatively unconstrained design space of newly designed systems results in a complicated SoS design space. In the case of legacy component systems with fixed designs, the SoS design may need to concentrate on the design of interfaces between them (Maier 1998).

Complicated stakeholder analysis, the dynamics of SoS composition and the possible inclusion of both legacy and new systems are important considerations for SoS design. In the following section, these three issues are illustrated using an example existing collaborative SoS.

Example SoS: Collaborating Astronomical Observatories

There are currently several active space-based and ground-based astronomical observatories operating over most of the electromagnetic spectrum. This large variety of observatories provides an ideal opportunity for astrophysicists to combine data for a target across several wavelengths, providing valuable insight into the physical basis underlying the observed phenomena, beyond what is possible through a single wavelength observation. This combining of multi-wavelength observation data is accomplished by coordinating observing between two or more observatories.

The observatories operate in coordination for a short period of time, creating a temporary SoS, after which they return to normal individual operations. Each observatory has its own set of observing constraints, value propositions and scheduling systems. This system of observatories can be considered a ‘collaborative SoS’, as the participation of the observatories is voluntary and only occurs when the perceived net benefit as seen by the decision makers of each observatory is above a certain threshold. Component systems may enter or leave the SoS completely, as older observatories die, and new observatories become available; component observatory capabilities may change over time as their spacecraft constraints change, e.g. the change from 3- to 2-gyro operating mode on the Hubble Space Telescope reduced its observing capability.

As an example to illustrate the SoS design issues described above, consider a simple coordination effort between two observatories: the Chandra X-ray Observatory and the Hubble Space Telescope (HST). Suppose the purpose of constructing this SoS is to obtain simultaneous observation of M31 in X-ray and UV and Optical wavebands, in order to provide useful astrophysical data to an observer who has requested it. For the observer, there is emergent value provided by the SoS – the availability of simultaneous multi-wavelength data is more valuable than single waveband data, or images in two wavebands taken at different times.

The component systems in the SoS are Chandra, HST and the observer. Chandra and HST provide observational data, which the observer then combines to derive scientific insight which is eventually passed on to the scientific community at large. The interface between HST and Chandra consists of the interactions between schedulers on both sides to determine a suitable timeslot for the observation. The interface between each of the observatories and the observer results when the observer officially requests observing time from the observatories before the SoS is constructed, and receives data from each after the observations are completed.

Each of the issues highlighted in the previous section now follow.

Stakeholder Analysis: The stakeholders at the local level are the Chandra operations team members, Chandra observers, HST operations team members, and HST observers. The SoS stakeholders are the observer who requested the coordination and the scientific community. The observer of M31 is part of both the local and global stakeholder set. In this multi-stakeholder scenario, alignment of the stakeholder objectives is not necessarily simple. As many of the primary decision makers are members of the general scientific community, the stakeholders are often in general agreement about the value of the SoS operation. Despite the agreement that there is global value in constructing the SoS, the perception of value and cost at the local level is different for each observatory. There may be significant reduction in local value delivery due to the incorporation of the observatory in the SoS, such as possible adverse effects on other observations due to scheduling of this coordination, as well as increase in costs, such as greater scheduling effort required from the schedulers at each observatory. Referring to eq (4) again, the observatory will participate in the SoS if the perceived net benefit gain is greater than the threshold for the local stakeholders. In this SoS, there is no centralized control, and no incentives offered to the observatories, so one or more of the observatories may choose to not participate.

Dynamics of SoS Composition. If the perceived net benefit for Chandra or HST decreases below their individual thresholds, either observatory may leave the SoS. On the other hand, if the perceived net benefit of another observatory, such as the XMM-Newton X-ray Observatory, increases above a threshold, that observatory may join the SoS. Additionally, observatory capabilities available to the SoS might change – for instance, due to a servicing mission to replace a camera, or changes in spacecraft operating constraints. Thus, the SoS is dynamic over its lifetime, which must be taken into consideration during the design of the system. In this coordination case, if Chandra leaves the collaborative SoS, HST can still produce local value by completing its own observation. Thus there is graceful degradation of the global SoS value to local value delivered by the individual component observatories if the SoS degrades.

Legacy and New Components. The SoS composed of Chandra, HST and the observer consists entirely of legacy components. The design of the observatories cannot be changed for the purpose of this SoS design, so the designer has control only over the design of the interfaces. However, NASA may decide to develop future missions for multi-wavelength observing, which might introduce clean-sheet component systems into the SoS. If a data repository is designed to convert and combine the data from multiple observatories, the SoS designer may have control over the design of both components and interfaces. Knowledge of design constraints of the SoS components and interfaces informs the designer about where to efficiently utilize design efforts.

Tradespace Analysis of Systems of Systems

The coordinating observatories example described above is a collaborative SoS which operates with a certain level of success. However, like most other systems of systems currently in existence, it is created on an ad hoc basis. There is a need for a prescriptive design methodology for SoS that will allow engineers to design SoS while taking into consideration the specific issues that make SoS design difficult. This section proposes to extend the Multi-Attribute Tradespace Exploration (MATE) methodology to SoS tradespace exploration, incorporating issues raised, and allowing for design and comparison of many SoS alternatives.

Multi-Attribute Tradespace Exploration. Multi-Attribute Tradespace Exploration (MATE) is a formal framework for tradespace exploration during system design (Ross 2003). This methodology allows the system designer to make both broad and deep trades between and among requirements and system concepts early in the design process, when the designer has the most leverage in terms of ultimate costs and benefits created by the system. MATE has been extended to deal with dynamic issues such as unarticulated stakeholder preferences, changing requirements and changing system context (Ross 2006).

Dynamic MATE is particularly suitable for extension to the SoS domain, as it already incorporates certain desirable qualities. MATE allows for comparison of multiple concepts within the same tradespace, which is crucial for SoS, which often include many diverse components. As the MATE methodology puts less emphasis on optimization, but rather provides a set of high benefit at cost solutions, the designer can observe the changes in benefits and costs that occur when the dynamic SoS changes. Dynamic MATE is a useful method to study changeability characteristics of the SoS over time, and can help identify designs that are value robust to changes in component system membership, expectations, and contexts over time. Epoch–Era Analysis, which is part of the dynamic method, can provide insight into when in the system evolution new systems may need to be added, and when investments should be made in new technologies. The Dynamic MATE method can be run with changed expectation levels and design concepts very easily and quickly, which is valuable for quick turnaround design or redesign of a SoS while it is in operation.

Proposed Enhancements to MATE for SoS

Based on the SoS issues that were identified and discussed earlier in the paper, Dynamic MATE can be developed further to provide an effective framework for SoS tradespace exploration. Over the next year, the proposed additions to Dynamic MATE will be implemented, and the method will be tested using a case study that is currently being performed with an industry partner. Application of this new SoS tradespace exploration method to the case study will help validate the usefulness of this method in real-world SoS engineering. The proposed enhancements to MATE address the three differences between SoS and traditional system engineering identified earlier: stakeholder analysis, dynamic SoS composition and the presence of legacy and new components.

Stakeholder Analysis. Due to a possibly large stakeholder set, a SoS designer is confronted with a multi-stakeholder problem during stakeholder analysis. Multi-stakeholder negotiations may require aggregating and trading the preferences of decision makers, depending on the relations between the local and global stakeholders. The designer must incorporate local and global distribution of costs and benefits into a multi-level value proposition for the SoS. The model of the 'likelihood of participation' discussed earlier relates the managerial control, benefit, cost and incentives in the SoS, and is the first step in developing the multi-level value proposition required for SoS design.

MATE studies to date have only considered a few stakeholders, usually focusing on the primary decision makers for the system (Derleth 2003; McManus et al. 2003; Roberts 2003; Ross 2003). In collaboration with an industry partner, a MATE case study with a larger number of stakeholders is currently being investigated. However, in order to have a generalized method for SoS, the stakeholder analysis process must be developed further.

Dynamics of SoS Composition. Epoch-Era Analysis is an approach applied in Dynamic MATE to analyze systems that operate in a dynamic context (Ross 2006). In Epoch-Era Analysis, the SoS lifetime can be divided into a series of epochs, which are defined as time periods when significant system design characteristics, expectations, and context variables are fixed. Multiple consecutive epochs can be strung together to create an era, which represents a longer run view of the system evolution. Within each epoch, static analysis can be done to evaluate various designs.

Significant changes in the SoS or the SoS context – such as a component system joining or leaving the SoS – can be represented by defining a new epoch. Path analysis within each epoch can help identify paths to designs that provide high value delivery to the SoS stakeholders. While a single epoch can give a SoS designer an idea of the short-term evolution of the SoS, arranging multiple epochs into longer periods called eras can provide a long-term view of the SoS evolution and help the SoS designer identify long-term strategies for sustaining the SoS. Epoch-Era analysis is a useful method for rapidly-evolving SoS, as the analysis can be quickly redone as strategy selection criteria and epoch boundary definitions change over time.

Enabling graceful degradation of SoS value delivery is an important consideration in SoS design. Epoch-Era Analysis may help identify SoS designs that are value robust, i.e. maintain a certain level of value delivery under changing conditions, such as component systems joining and leaving the SoS, and help SoS designers devise strategies to transition to such designs.

Legacy and New Component Systems. SoS are often composed of both legacy and new systems, as well as existing and newly-designed interfaces between component systems. The SoS designer may not have the ability to affect enhancements and upgrades to legacy systems or interfaces. The 'system shell' concept (Ross et al. 2007) may be a useful construct when the component system design cannot be altered. By designing a wrapper or shell around the legacy component, it can easily be integrated into the SoS and interfaced with other components without adversely affecting the legacy operation. This concept may also make it easier to switch components in and out of a SoS with minimum impact on the SoS operation.

The application of Epoch-Era Analysis to system timelines in order to identify value robust designs is an active area of research (Ross et al. 2008). Further development of stakeholder analysis and Epoch-Era Analysis will result in a Dynamic MATE tradespace exploration method that is suitable for SoS design.

In the coming months, the proposed enhancements to extend the MATE method to SoS will be further developed. In an ongoing project with an industry partner, MATE is being applied to develop an operationally responsive disaster recovery observation system. Through this project, MATE is being extended to multi-stakeholder system design and is being further validated in a practitioner setting. In the near future, this project will utilize SoS concepts and will work as a test case for the Dynamic MATE SoS tradespace analysis method that will be developed based on the ideas presented in this paper.

Conclusion

There are differences in design considerations between traditional systems and Systems of Systems. Multi-level multi-stakeholder analysis, dynamic SoS composition and the utilization of both legacy and new component systems require the development of new system engineering methods to tackle the challenges of SoS design. Defining a control-influence relationship between the SoS designer and component systems is a step towards quantifying SoS characteristics, and extending the Dynamic MATE methodology for tradespace exploration of SoS designs. An effective SoS tradespace exploration methodology will include multi-level value propositions for multiple stakeholders, a time-varying component system set and an understanding of the changing system context. Dynamic MATE, when extended by the proposed enhancements, will provide an effective framework for SoS tradespace exploration and analysis.

Acknowledgements

The authors gratefully acknowledge the funding for this research provided by the Systems Engineering Advancement Research Initiative (SEAri), a research initiative within the Engineering Systems Division at the Massachusetts Institute of Technology. SEAri (http://seari.mit.edu) brings together a set of sponsored research projects and a consortium of systems engineering leaders from industry, government, and academia. SEAri gratefully acknowledges the support of Draper Laboratory in this research.

References

DeLaurentis, D.A., "Understanding Transportation as a System-of-Systems Design Problem", AIAA, Reno, Nevada, 2005.

Derleth, J.E., *Multi-Attribute Tradespace Exploration and Its Application to Evolutionary Acquisition*, S.M., Massachusetts Institute of Technology, 2003.

DoD AT&L, "System of Systems Systems Engineering Guide: Considerations for Systems Engineering In a System of Systems Environment," Deputy Undersecretary of Defense (Acquisition and Technology), Office of the Undersecretary of Defense (Acquisition, Technology, and Logistics), v. 9, DoD, 2006.

Keating, C., Rogers, R., Unal, R., Dryer, D., Sousa-Poza, A., Safford, R., Peterson, W. and Rabadi, G., "System of Systems Engineering", *Engineering Management Journal*, 15, 3, pp 36-45, 2003.

Maier, M.W., "Architecting Principles for Systems-of-Systems", *Systems Engineering*, 1, 4, pp 267-84, 1998.

McManus, H.L. and Schuman, T.E., "Understanding the Orbital Transfer Vehicle Trade Space", AIAA Space 2003 Conference and Exposition, Long Beach, CA, 2003.

Roberts, C.J., *Architecting Evolutionary Strategies Using Spiral Development for Space Based Radar*, S.M., Massachusetts Institute of Technology, 2003.

Ross, A.M., *Multi-Attribute Tradespace Exploration with Concurrent Design as a Value-Centric Framework for Space System Architecture and Design*, S.M., Massachusetts Institute of Technology, 2003.

Ross, A.M., *Managing Unarticulated Value: Changeability in Multi-Attribute Tradespace Exploration*, Ph.D., Massachusetts Institute of Technology, 2006.

Ross, A.M. and Rhodes, D.H.,"The System Shell as a Construct for Mitigating the Impact of Changing Contexts by Creating Opportunities for Value Robustness", IEEE Systems Conference, Honolulu, HI, 2007.

Ross, A.M and Rhodes, D.H.,"Using Natural Value-Centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis," SEAri working paper WP-2007-1-3, http://seari.mit.edu, November 2008.

Sage, A.P. and Cuppan, C.D., "On the Systems Engineering and Management of Systems of Systems and Federations of Systems", *Information Knowledge Systems Management*, 2, pp 325-45, 2001.

Shah, N.B., Rhodes, D.H. and Hastings, D.E., "System of Systems and Emergent System Context ", Conference on Systems Engineering Research, Hoboken, NJ, 2007.

Biographies

Debarati Chattopadhyay. Debarati Chattopadhyay is a Masters Candidate in the MIT Aeronautics and Astronautics department. Prior to pursuing a graduate degree, she worked as a Science Mission Planner for the Chandra X-ray Observatory at the Harvard-Smithsonian Center for Astrophysics. Deb has B.S. degrees in Astrophysics and Computer Engineering (Lehigh University ’04, ’05).

Adam M. Ross. Dr. Adam M. Ross is a Research Scientist in the MIT Engineering Systems Division and is one of the co-founders of the MIT Systems Engineering Advancement Research Initiative (SEAri). Dr. Ross has work experience with government, industry, and academia, performing both science and engineering research. He has published papers in the areas of space systems design and changeability, and has interests in the areas of managing unarticulated value, designing for changeability and value robustness, and dynamic tradespace exploration for complex systems. He holds a B.A. in Physics, and Astronomy and Astrophysics from Harvard University, and a M.S. in Aeronautics and Astronautics, M.S. in Technology and Policy, and Ph.D. in Technology, Management, and Policy of Engineering Systems from MIT.

Donna H. Rhodes. Dr. Donna H. Rhodes is a Senior Lecturer and Principal Research Scientist in the MIT Engineering Systems Division. Previously, Dr. Rhodes held senior management positions in several corporations. She is a co-founder of the MIT Systems Engineering Advancement Research Initiative (SEAri), directing its research program and advising graduate students. She also leads research in enterprise systems engineering for the Lean Advancement Initiative at MIT. She is a Past President, Fellow, and Founder of INCOSE, and director of the SEANET doctoral student network. She has published numerous papers in the field of systems engineering. Her research focuses on architecting and design of complex systems, systems-of-systems, and enterprises. She holds a M.S. and Ph.D. in Systems Science from T.J. Watson School of Engineering at Binghamton University.