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System-of-Systems Acquisition: Alignment and Collaboration

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System-of-Systems Acquisition: Alignment and Collaboration

11 October 2011

by

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ACQUISITION RESEARCH PROGRAM
GRADUATE SCHOOL OF BUSINESS & PUBLIC POLICY
NAVAL POSTGRADUATE SCHOOL

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Abstract

System-of-systems (SoS) acquisition research has identified lack of alignment and lack of collaboration as two important issues leading to problems in SoS acquisition. This report captures the exploratory work toward improving alignment between and collaboration among the individual system programs in the development of an SoS. An SoS inter-program collaboration approach is proposed. It is inspired by some existing web-based collaborative systems, such as eBay, Facebook, and Eureka, and suggests an attraction mechanism to effect SoS inter-program collaboration. In addition, a web-based collaborative system is also suggested. Based on an architecture for distributed and interoperable management of multi-site production projects, it allows personnel of all programs associated with an SoS to input need points for component system inputs and retrieve information required to align the individual programs. Furthermore, contracting structures for facilitating collaboration among the system programs are also considered. Finally, this work forms a basis for implementing a web-based SoS collaborative system to support Department of Defense (DoD) SoS acquisition programs.

Keywords: System of systems (SoS), inter-program collaboration, inter-organizational collaboration, web-based collaborative system, contracting structures, SoS acquisition, attractor mechanism, emergent behavior, collaborative capacity, SCEP model

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I.   Introduction

The most common type of Department of Defense (DoD) systems of systems (SoS) development is one in which an SoS is created by integrating separately developed systems—legacy systems, developmental systems, or some combination of both. Research in SoS acquisition has identified lack of alignment and lack of collaboration as two important issues leading to problems in SoS acquisition. Lack of alignment means a system is not ready for its integration into an SoS or, because of the lack of the front-end SoS systems engineering (SE), the SoS integration discovers that the system does not meet the performance requirements or the interface requirements. Lack of collaboration means the individual system programs fail to work with each other to achieve the goals of the SoS program.

SoS acquisition requires the availability of surrogates of component systems, and later of the "as-built" component systems, in a timely manner in order to support SoS integration testing. However, the acquisition schedules for the component systems are typically developed independently of the SoS development schedule. There is, thus, no assurance that the SoS integration testing can be completed as planned, resulting in a slip of the SoS acquisition schedule and an associated cost overrun. Even when the schedules are aligned, a lack of the front-end SoS SE may cause a system to not meet the performance or interface requirements during the SoS integration or there may be misalignment of resources to support SoS integration testing, such as, for example, the absence of component system experts to support SoS integration testing.

The lack of alignment is related not only to the front-end SoS SE in the SoS acquisition, but also to the lack of collaboration. Collaboration in the development of an SoS is multi-dimensional; that is, it must exist between DoD system program offices, between contractors, and between DoD program offices and contractors. "Inter-organizational collaboration has been cited as a critical requirement for successful outcomes; and for those agencies struggling to achieve their goals, lack

of inter-organizational collaboration has been cited as a factor accounting for failure" (Kirschman & LaPorte, 2008). Inter-organizational collaboration requires collaborative capacity. Mirroring the definition of collaborative capacity by Hocevar, Jansen, and Thomas (2007), collaborative capacity in SoS acquisition is defined as the ability of the individual system programs to enter into, develop, and sustain inter-system programs in the pursuit of SoS collective outcomes. Such collaborative capacity is needed, in addition to contracting structure and organizational structures (Rendon, Huynh, & Osmundson, 2010; Huynh, Rendon, & Osmundson, 2010), to effect resolution of the SoS acquisition issues raised in Osmundson, Huynh and Langford (2007). These issues are initial agreement, SoS control, organizing, staffing, team building, training data requirements, interfaces, risk management at the SoS level, SoS testing, measures of effectiveness, and emergent behavior. For this report to be self-contained, a brief explanation of these issues, excerpted from Rendon, Huynh, & Osmundson (2010) and Huynh, Rendon, & Osmundson (2010), follows.

- Initial agreement refers to decision makers initially getting agreement that an SoS meets some desirable objectives. It is an issue in particular when the SoS involves systems from different organizations or services because establishing an initial agreement is contingent on quantifying the benefits and risks of the new SoS.

- SoS control must be established: Who will control the SoS and how it will be controlled. Each partner may lose some measure of control over its own systems in order to enable overall SoS control.

- Organizing is a key issue of how to organize for the development and operation of an SoS. An example is the systems engineering process: How are processes that interface with SoS processes established and monitored?

- Staffing, team building, and training refer to how an SoS will be staffed and operated. SoS operations must be planned for, the skills required for SoS operations identified, and personnel with the proper skills acquired and trained in SoS operations.

- Data requirements is an issue concerning sharing of classified and/or proprietary design information among the SoS partners, who must

recognize and weigh a possible loss of their system's operational superiority based on the shared classified or proprietary design information against the SoS benefits.

- Interfaces must be identified and managed. Common language, grammar, and usage must be established (for information SoSs); configuration management invoked to assure common agreements are followed; and required information security levels identified and provisions made to assure meeting of security requirements.

- Risk management at the SoS level is an issue related to the mitigation of SoS risks potentially affected by component systems; the risk mitigation requires detailed knowledge of component system risks and variations in individual system outputs.

- SoS testing requires that each SoS partner's system be tested in a manner that resolves any of its concerns about operational behavior and that SoS threads be tested.

- Measures of effectiveness is an issue because their strong dependence on individual component systems' measures of performance requires an understanding of the latter, and this issue is related to the issues of data requirements and interfaces.

- Emergent behavior, exhibited by the SoS, resulting from unknown interactions among the constituent systems or from its interaction with the environment, need to be collectively understood, analyzed, and resolved, in particular when an emergent behavior may be detrimental to one or more of the partners.

The SoS acquisition issues addressed in this report are not just the ability of individual system programs to enter into, develop, and sustain inter-systems programs, but also the approach to and mechanism of inducing or motivating the individual system programs to develop and maintain such an ability. The mechanism is intended to remove barriers against and implement factors favorable to the realization of collaborations among the individual system programs. The approach proposed in this work to bring about collaboration among the individual system programs is to combine this mechanism with a web-based system to aid in managing their collaboration as well as to implement a front-end SoS SE in the SoS acquisition. As the lack of alignment is tied to both the lack of the front-end SoS SE in the SoS acquisition and the lack of collaboration, the collaboration brought about

by this approach in turn aids in improving the alignment of the individual system programs.

Due to constraints in the scope of this report, the front-end SoS SE in the SoS acquisition is not discussed here. This report is focused only on collaboration among the individual system programs as it is related to the misalignment issue. A discussion of front-end SoS SE in the SoS acquisition can be found in Huynh, Rendon, and Osmundson (2010). . Furthermore, Heng (2011) conducted a quantitative analysis of the benefits of having the front-end SoS SE in the SoS acquisition.

Enhancement of program collaborations might include re-organization of program structures, creation of new program structures, creation of new contracting structures, and use of incentives. These techniques, however, are not necessarily the only means to effect enhancement of program collaborations. In this work, the key idea underlying the proposed approach is the collaborative behavior observed on some existing web-based systems. That is, what has been done with web-based collaborative systems is extended to a web-based system that will facilitate the development of an SoS through collaborative behavior from the individual system programs. It is the web-based system concept that inspires the mechanism proposed in this research for inter-program collaboration.

System-of-systems (SoS) modeling and simulation has recently been applied to the problem of engineering SoSs in order to prevent undesired emergent behavior (Osmundson, 2009). Example SoSs that have been studied are the collateralized debt obligation market (Osmundson, Langford, & Huynh, 2009) and the North American electric power grid (Osmundson, Huynh, & Langford, 2008). Theoretical studies of these SoSs have also been carried out to validate the results from the modeling and simulation work (Huynh & Osmundson, 2008; Huynh & Osmundson, 2009). The results of these studies indicate that SoS modeling and simulation can be used, at least in some cases, to predict undesired emergent behavior in SoSs

that consist of engineered systems and non-engineered systems, including people, and to identify ways to prevent or mitigate undesired behavior.

Essentially, to deal with the lack of alignment and collaboration in SoS acquisition, an SoS acquisition program needs to institute an overarching front-end SoS SE in the SoS acquisition program and to implement an approach to achieving collaboration among the individual system programs.

In this report, a web-based collaborative system (WBCS) is proposed, on which personnel of all programs associated with an SoS can input and retrieve information required to align the individual programs.   As discussed in detail later in this report, the proposed collaborative web-based system is based on the concept of an architecture for distributed and interoperable management of multi-site production projects espoused in Ishak, Archimede, and Charbonnaud (2010).   The kernel of this system is the SCEP (Supervisor, Customer, Environment, Producer) model (Archimede & Coudert, 2001).   Based on multi-agent systems (Ferber, 1999), the SCEP allows a distributed management of acquisition programs (i.e., system programs and the SoS program) and their cooperation via a shared environment. The overall development of the SoS and component systems is treated as a network and the need points for component system inputs are identified as intermediate milestones requiring SoS-component system collaboration. An attraction mechanism to effect SoS inter-program collaboration is incorporated in this web-based SoS collaborative system.

The purposes of this report are to

- discuss in some detail some existing web-based collaborative systems;

- explain our exploratory work toward improving alignment between and collaboration among the individual system programs in the development of a system of systems;

- elucidate the approach proposed in this research for achieving collaboration among the individual system programs; and

- discuss contracting structures motivating or facilitating collaboration among the system programs.

The rest of the report is organized as follows. First, the web-based collaborative systems are described and explained. Modeling and simulation of the web-based collaborative systems are discussed next. The SoS inter-program collaboration approach is then explained. A discussion of contracting structures for facilitating collaboration among the system programs follows. Finally, the report ends with some concluding remarks.

II.   Web-Based Collaborative Systems

A.   The Underlying Idea of Web-Based Collaborative Systems

Many web-based systems are based on what is known as network effect (Liebowitz & Margolis, 1995). When the network effect is present, the value of the system to customers or collaborators is, thus, dependent on the number of customers or collaborators already using the system.

Network effects become significant after a certain number of people have subscribed to the system, called the critical mass. At the critical mass point, the value obtained from the good or service is greater than or equal to the price paid for the good or service. Cost is also incurred in using a web-based system. Cost could be the payment of money for a service or product, time to prepare inputs for the system, time spent using the system before a match is found, or a loss associated with the risk of using the system, such as not receiving goods paid for, receiving incorrect goods, or some other loss. There may also be some cost associated with attracting the participants. At the critical mass point, the value obtained from the system is greater than or equal to the cost encountered when obtaining the good or service provided by the system. As the value of the good is determined by the user base, this implies that after a certain number of people have subscribed to the service or purchased the good, additional people, because of the positive value/cost ratio, will subscribe to the service or purchase the good.

Prior to reaching the critical mass, and depending on the system type, the system must attract early adopters by investment capital, incentives, or other means. In the interim, before the critical mass is achieved, some early adopters may drop out of the system because of lack of perceived value, while others join the system. Thus, the success of a web-based system depends on achieving a critical mass of subscribers before the effectiveness of attracting additional subscribers to the system is exhausted.

The system factors that determine the success or failure of a web-based system include the number of subscribers or participants as a function of time; the factors that attract a subscriber; the factors that cause a subscriber to leave the system; the value of the system's services to the subscriber/participant; and the cost of the system's services or products to the subscriber/participant. The term "participant" will be used exclusively hereafter, as the individual system programs are "participants," although in a strict sense the term "subscriber" more properly refers to someone who pays for a service, while a participant refers to a person who invests time and effort to obtain a product or service, but does not pay money for it.

B. Examples of Collaborative Systems

The type of web-based system of most interest is a collaborative enterprise whose success depends on the number and quality of the participants, but not on how much revenue the system attracts. Examples of this type of system are those that are established to facilitate a process through collaborative behavior, such as eBay, Facebook, and the Xerox Eureka system.

eBay is an online auction and shopping website on which individuals and businesses buy and sell a wide variety of products and services. eBay was founded in 1995 and experienced very rapid growth. By the second year of operations, eBay hosted 250,000 online auctions and two million online auctions the following year (www.en.wikipedia.org). Facebook is a social networking website that began in February 2004 and had more than 500 million participants by July 2010 (Facebook 2011). Participants maintain personal profiles, add people as friends, send messages to friends, notify friends about updates to their profile, and access friends' profiles. The Eureka system, developed by Xerox (Choo, n.d.), allows customer service engineers for Xerox's family of copier machines to share validated tips on problems encountered and solutions to these problems. The system is an example of a net-based community of practice within an organization. Customer service engineers browse the Eureka system to see if there is a known solution to a problem that they are encountering. Five years after its introduction, the Eureka system had

been widely adopted by Xerox technicians and has resulted in significant savings in time and parts costs (Bobrow & Whalen, 2002).

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III.   Modeling and Simulation of Collaborative Systems

The SoS modeling and simulation (M&S) approach discussed in the Introduction section is used to model a system of individual system programs collaborating to form an SoS. This M&S approach has been illustrated with eBay, Facebook, and Eureka (Osmundson & Holgerson, 2011). To be self-contained, this report briefly discusses the M&S approach and results of these collaborative systems. This M&S approach considers a collaborative system to consist of people, databases, and other elements. People interact with one another directly, through databases and/or other elements, to achieve outcomes.

Three types of discrete-event models represent eBay, Facebook, and the Xerox Eureka system. Each model assumes a specific type of attraction mechanism, unique to each system, which attracts sufficient users over time, resulting in a successful system whose value exceeds its costs. In Figure 1, the users interact with other users and/or the web-based system. In each case, there is a small initial seed population of users. If the users are attracted to one another and/or to the system in sufficient numbers, over time a successful net presence ensues. The key to this type of system is the attractor mechanism, which is the mechanism that provides value to the users, while at the same time a cost is imposed on the users. The cost could be a monetary fee and/or—more likely in many cases—the time and effort required to participate in the system and the potential risk in participating in the system. Each of the models of the three types of systems is implemented in Extend,[1] a discrete-event modeling and simulation tool, and the results of each of the three types of models agree closely with real-world data.

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[1] Extend is a product of Imagine That Inc., 6830 Via Del Oro, Suite 230, San Jose, CA 95119 USA.
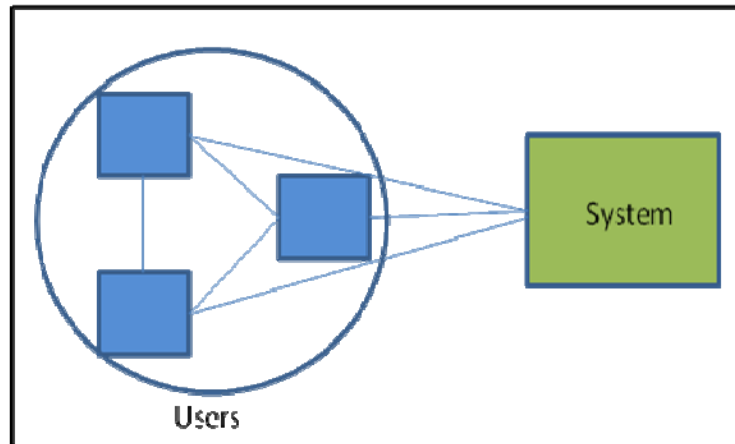
**Figure 1.   Abstract Form of Web-Based Systems Model**

Cost and value are specific to each example system. As the eBay model represents online sellers and buyers of a variety of goods, the value to the seller is low cost of sales and, potentially, a large number of buyers, and the value to the buyer is a wide selection of goods at low prices. These values are functions of the number of users over time; as the number of sellers and buyers increases, the value to both parties increases. There are also costs to the seller and buyer. The seller is at risk of not being paid and the buyer is at risk of not getting the goods at all or of getting miss-represented goods and/or suffering identify theft. Initially, these risks were relatively high, but as improvements were made to eBay over time, such as the introduction of seller ratings and use of PayPal, these risks declined. Thus, the value-to-cost ratio can be represented by the time-dependent number of eBay users and an S-curve function representing declining risk over time. The rate at which sellers enter the system is dependent on the number of buyers in the system. The buyers' risk factor is given by an S-curve function. A detailed discussion of the simulation results of the Extend eBay model, as well as the Extend Facebook model and the Extend Eureka model, is provided in Osmundson and Holgerson (2011). In this report, it suffices to point out the similarity, as shown in Figure 2, between the simulation results and the eBay user growth data.
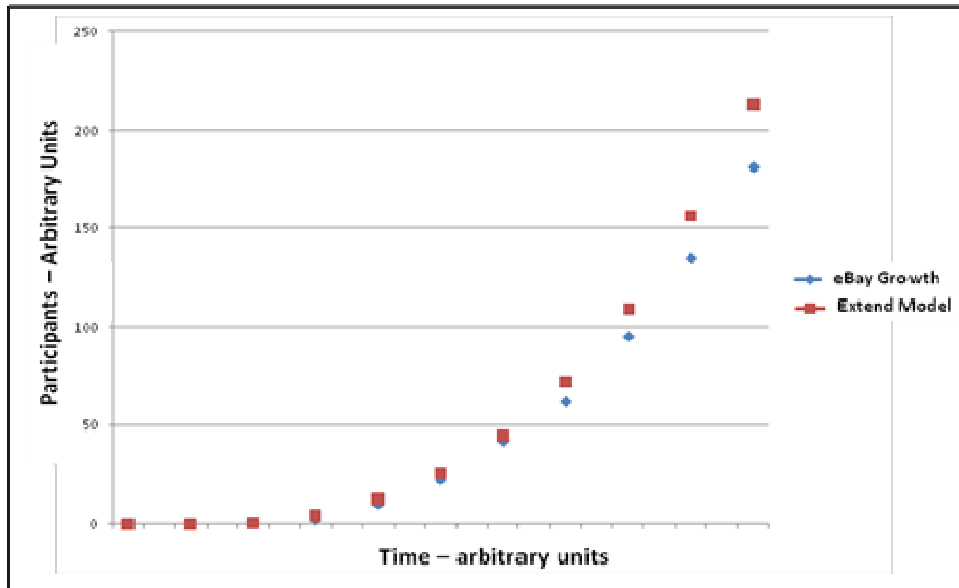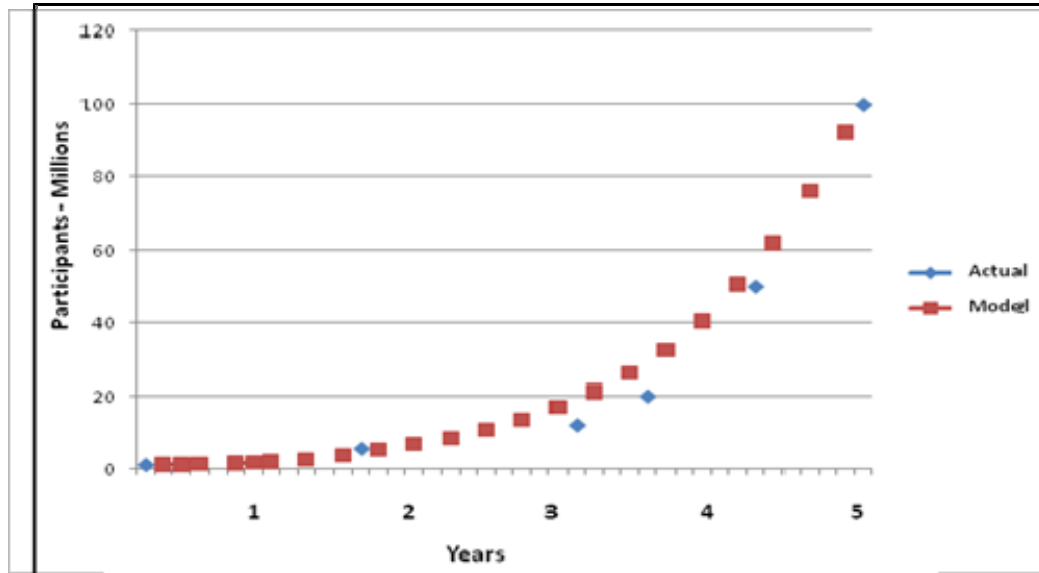
Figure 2. Results of the Extend eBay Model
(Site Analytics, 2010)
Note. Red markers are model results, and blue markers are eBay actual growth numbers.

The Facebook model represents people who want to form social networks with their friends. The value to each individual is the ability to communicate on a regular basis with a large number of friends by posting text and pictures to their Facebook homepage, which can be viewed by their friends. Value increases with the number of friends added up to a point where the cost of maintaining meaningful connections is outweighed by the incremental value of adding additional friends or becoming a friend on another person's site. There is an initial population of participants, and new participants arrive at a rate proportional to the total population. Participants look for a match—that is, a friend—and the probability of finding a friend is proportional to the total population. As shown in Figure 3, the Extend model results fit the actual Facebook population data fairly well through the first 41 months, but beyond that point the model population grows at a rate faster than the actual population. The Extend model is a very simple model and does not include any saturation effects such as might occur if the early adopters of Facebook were more likely to find friends among a given population than were late arrivals, or if the Facebook population began to approach a limit of all possible networked users.

Figure 3. Results of the Extend Facebook Model
Note. Red markers are model results, and blue markers are Facebook actual growth numbers. This figure was created by the authors using data retrieved from Facebook.

The Eureka model begins with generation of experts who initially are assigned problems randomly; the experts then enter tips for solving each of the problems. This generates an initial set of validated tips. Other technicians are generated next. The experts are randomly assigned new problems; they check the database for tips, and, if a tip exists, they utilize it and solve the problem quickly. If no tip exists, they take a long time to solve the problem and, with some probability, either enter a new tip or not. The probability of entering a new tip is given by an S-curve function that is dependent on the number of times a given person's tips have been utilized. This reflects the fact that technical workers are highly motivated by peer recognition and is consistent with Xerox's experience.

The Eureka model was initially run and the probability with which technicians checked the database was adjusted until a best fit was obtained with real-world data. The best fit occurred when the probability of checking the database at a given time was set to 0.4T/P, where T is the number of tips generated up to a given time, and P is the total number of problems that are expected to be encountered. Based on available data on Xerox's Eureka system, the initial number of tips was 100–200

(Choo, n.d.), the total number of technicians during the first five years of use was 19,000, the number of technicians participating in the Eureka system after five years was 15,000, and the total number of unique vetted tips after five years was 36,000. The total number of problems to be solved was not available; for purposes of calibrating the model, the total number of problems was assumed to be 50,000. It was also assumed that it took an average of one hour to solve a problem with a tip and an average of eight hours without a tip and that technicians completed approximately one trouble call per day. Jack Whalen, a scientist who worked on many of Xerox's collaborative information systems while at Xerox's Palo Alto Research Center from 1994-2010 (personal communication, October 14, 2010) estimated that non-routine problems occurred more frequently than once per week, but less frequently than once per day.

The most important measure of effectiveness of this type of system is the participation rate. The participation rate drives the number of new tips generated over time and is the main factor in determining the reduction in time to solve problems. Participation rates at the end of one year and at the end of five years, as a function of initial tips and total expected problems, are shown in Figures 4 and 5, respectively. The results clearly show that the ratio of initial tips to number of expected problems to be encountered is critical to success, particularly in achieving a reasonably high rate of technician participation.
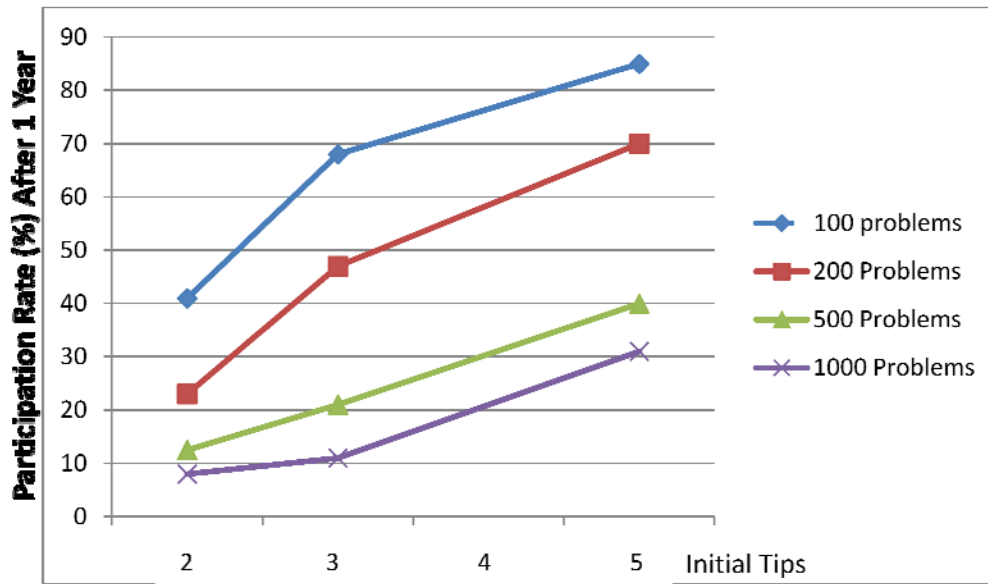
Figure 4.   Participation Rate After One Year as a Function of Initial Tips and Number of Problems to be Encountered
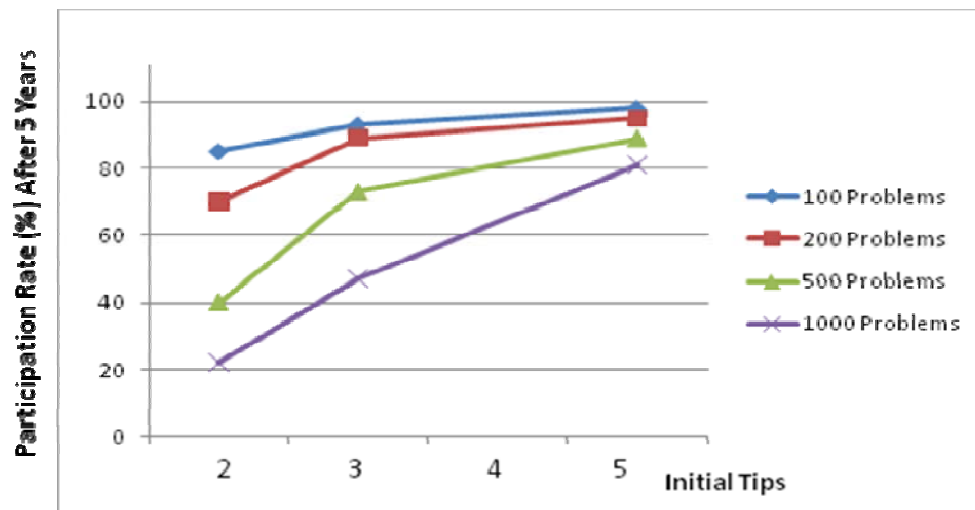
Figure 5.   Participation Rate After Five Years as a Function of Initial Tips and Number of Problems to be Encountered

IV. SoS Inter-Program Collaboration Approach

There are two parts to the approach espoused in this work: developing a web-based collaborative system and exploring contracting structures to facilitate the participation of the individual system programs in this system. Both make use of incentives for or attractors to the use of the web-based system.

As discussed in the Introduction section, collaboration among the individual system programs participating in an SoS acquisition depends on the presence of mechanisms to induce the willingness on the part of the individual programs to collaborate and to enable their collaboration. Mechanisms can include formalized structures for coordination; formalized processes including meetings, deadlines, etc.; sufficient authority of participants; clarity of roles; and assets such as personnel who are dedicated for collaboration. Lateral mechanisms can include interpersonal networks, effective communication and information exchange, technical interoperability, and training (Hocevar, Thomas, & Jansen, 2006). As discussed in the Modeling and Simulation of Collaborative Systems section, a web-based system is an efficient means of providing a mechanism that provides many of the mechanistic requirements for collaboration. However, successful web-based collaboration is highly dependent on the value/cost ratio that applies to a given system.

Like eBay, Facebook, and Eureka, the collaborative system envisioned for SoS acquisition needs to have an attraction mechanism—to attract the individual programs to collaborate with the other programs to achieve the objectives of the SoS acquisition program. Such a mechanism, just like those implemented with eBay, Facebook, and Eureka, should be highly related to the cost and value of collaboration, as it provides value to the participating programs while at the same time a cost is imposed on them.

Each individual program invariably is burdened with the production of a system with required performance on schedule and within budget. Consequently, the value and cost derived from collaborating with the other programs are related to these parameters—performance, schedule, and budget. There is also, however, another element that can highly motivate participation in a collaborative system—recognition. Value is in terms of recognition. In the Eureka system, if technicians see that another worker has been recognized for providing a tip for solving repair problems, they, too, will want similar recognition and will be motivated to enter a new tip. If a technician sees that his own tip has been useful to others, he will be motivated to provide additional tips in order to achieve further peer recognition. Thus, in addition to promoting value and compensating for cost, recognition should be instituted for contributing to the development of the SoS acquisition. But, in what form should recognition be realized—money, promotion, reputation, rewards beyond a program manager's tour on the program? And to whom should recognition be attributed—just to the program managers, or to the entire team?

Some contributors to the cost of collaboration, hence the barriers to collaboration, are observed. A contributor is the cost of dedicating their resources to developing the parts that are required to satisfy the SoS requirements. The cost to program personnel collaborating in this effort is the additional time spent on executing the SoS part of the system. Another contributor is the cost associated with a potential delay in the development of their own systems, caused by their participation in the SoS development. The individual programs that are not compensated for these costs will more than likely decline to participate or pay lip service to collaborating in the SoS acquisition. This problem can be solved with new contracting structures, which will be discussed in Section VI.

A.   Attraction Mechanism

Assessing value for collaborating is more problematic. There is high value to the overall SoS through keeping the individual system programs aligned in order to support SoS testing, but there is not necessarily much value to each individual

component program. Program managers are typically rewarded for producing the desired system on time and within budget, but they are not presently rewarded for aligning their programs with other programs. Value to individual program managers and program offices must be provided in order to achieve effective collaboration.

The system factors that determine the success or failure of this collaborative SoS acquisition system include the number of participating programs, which depend on the aforementioned incentives; the factors that attract a collaborator; the factors that cause an individual program to continue to buy into collaboration; the values of the SoS to the participating programs; and the cost or risks to their programs.

The architecture of the system, its development process, and the organization that manages the system should "fit" each other. What an organization produces and how the organization is structured should at least be related to each other (Rechtin, 2000). In order to be effective, the structure of an SoS program office must match the architecture of the SoS and the SoS development process. Currently, the structures of most—or perhaps all—SoS program offices do not match SoS architectures and development processes. Since it is unrealistic to reorganize individual program offices in disparate Services into an overarching program office, the match can be made by creating a virtual organization that is linked by the web-based collaborative system (WBCS).

The AMF(Airborne, Maritime and Fixed) Joint Tactical Radio contract, received via personal communication, has been examined to identify the Contract Data Requirements Lists (CDRLS) that are examples of information required in the WBCS. The AMF CDRLS that impact the alignment of AMF with associated systems include the following:

- Integrated master schedule

- Risk/opportunity management plan
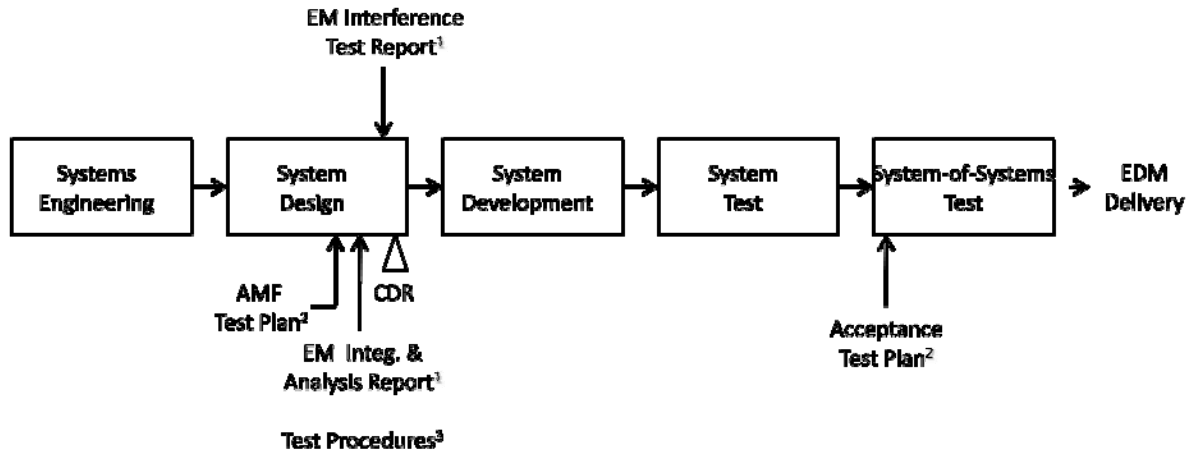
- Interface design description

- Test plan—AMF due not later than (NLT) 90 calendar days prior to Critical Design Review (CDR)

- Acceptance test plan—due NLT 240 calendar days prior to first GOVT EDM (Engineering Development Model) delivery

- Electromagnetic environmental effects integration and analysis report—initial submittal—due NLT 60 calendar days prior to CDR

- Electromagnetic interference test report—due NLT 45 calendar days after test event

- Test procedures—due NLT 60 days prior to CDR

- Software requirements specification

- TEMPEST control plan

- TEMPEST test plan

- Management plan

- Configuration management plan

- Test inspection report—due NLT 45 calendar days after each formal Contractor Test event

The required submission dates of selected CDRLS from the above list are as follows:

- Test plan—due NLT 90 calendar days prior to CDR

- Acceptance test plan—due NLT 240 calendar days prior to first delivery of the engineering development model to the government

- Electromagnetic environmental effects integration and analysis report—initial submittal due NLT 60 calendar days prior to CDR

- Electromagnetic interference test report—due NLT 45 calendar days after the test event

- Test procedures—due NLT 60 days prior to CDR

These need times are points where inputs are also required from the systems that are a part of the SoS. The general timeline for the AMF program is shown in Figure 6 with key need points identified.

EM Interference
Test Report[1]

| Systems Engineering | System Design | System Development | System Test | System-of-Systems Test | EDM Delivery |

AMF Test Plan[2]   CDR

EM Integ. & Analysis Report[1]

Test Procedures[3]

Acceptance Test Plan[2]

Required Inputs:
[1] Related programs' detailed design descriptions
[2] SoS systems engineering analysis
[3] Related programs' detailed designs and test plans

Figure 6.   AMF Sequence of Top-Level Activities and Approximate CDRL Need Times

Figure 7 illustrates the possible relative schedules of programs A and B whose systems A and B are intended to be part of the AMF SoS.
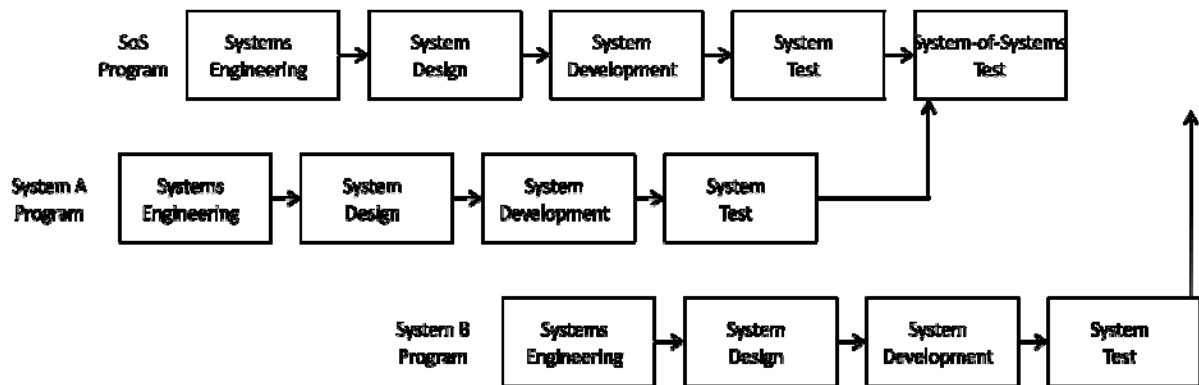
Figure 7.   An Example of the Relative Sequence of Activities of the SoS Program and Related Programs

Just as the integration of a system requires the alignment of the constituent components, a key need for SoS alignment is to integrate the constituent systems into the overall SoS.

Reporting requirements to achieve effective alignment and SoS integration can now be related to attractor mechanisms related to an online collaborative system. Figure 8 shows a high-level view of an online collaborative system and the required collaborations.
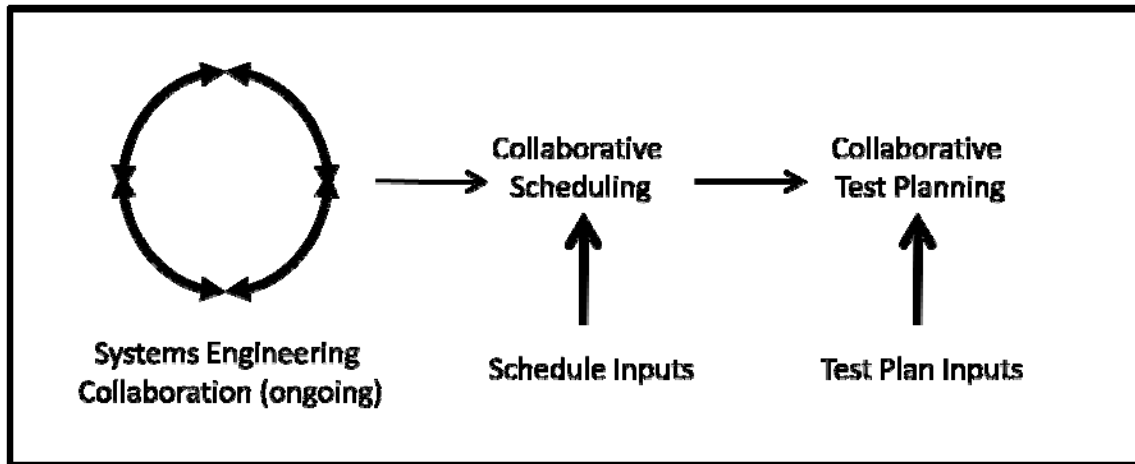
Figure 8. High-Level View of an Online Collaborative System and Required Inputs

As aforementioned, the attractor mechanism that encourages participation in an online system depends on the value to the participant and the cost to the participant.

The cost to the SoS program office for procuring a collaborative software system is modest and such a system is available commercially from numerous vendors, including Adobe, IBM, Microsoft, Siemens, and Oracle, among many others. Typical products offer the following features:

- Customizable meeting rooms

- Multiple meeting rooms per user

- VoIP

- Audio integration

- Video conferencing

- Meeting recording

- Screen sharing

- Notes, chat, and white boarding

- User management, administration, and reporting

- Polling

- Document depository and content library

Hocevar, Jansen and Thomas (2006) identifies the following driving forces of collaboration:

- Formalized structure for coordination

- Formalized processes, such as meetings

- Interpersonal networks

Video conferencing, in particular, encourages formation of interpersonal networks and virtual team building through virtual face-to-face meetings.

The SoS program office will also incur installation and training costs, which are typically modest, especially compared to typical SoS program budgets. Costs to the individual associated programs include training costs and time required to participate in the online system. There is no additional documentation burden on the individual systems. The collaborative system does not require the individual programs to input information other than what they are required to generate under their individual contracts, and the inputs do not have to be in any special format.

Value to the SoS program office means achieving alignment and reducing schedule risk and potential additional cost. As mentioned in the case of Xerox's Eureka system, systems engineers are likely to find value through peer recognition obtained by collaborating with other systems engineers. Schedulers and test planners may find the same type of value through peer interactions. A need for technical workers is supported by motivational theory as well as empirical evidence, such as the Eureka case. Maslow's motivational theory (Maslow, 1943) supports the

idea that technical workers who are high on the levels of satisfied needs are motivated by peer recognition. Lawrence and Nohria (2002) identify a four drives theory of individual motivation:

1. Drive to acquire (take, control—objects, status, recognition)

2. Drive to bond

3. Drive to learn

4. Drive to defend

Note that the drive to acquire recognition is equivalent to Maslow's 4th-level need, which is to be held in esteem by others—a need commonly shared by technical workers.

McShane and Von Glinow (2007) introduce the expectancy theory of motivation:

- E–to–P: An individual's perception that his effort (E) will result in a particular level of performance (P).

- P–to–O: An individual's perceived probability that a certain level of performance (P) will lead to particular outcomes (O).

- Outcome valence is the anticipated satisfaction that a person feels toward an outcome; the valence could be on a scale of -1 to +1 or -100 to +100.

P–to–O can be improved by rewarding high performance with something that the individual values highly. Since technical workers value peer recognition very highly, participation by the technical workers in a WBCS can be enhanced by the simple expedient of providing high visibility in the WBCS for workers' effective participation, much like in the Eureka system.

However, there is no apparent value to the individual program managers. A program can be thought of as an organization whose effectiveness is measured by its ability to draw needed resources, mainly funds to keep the program progressing. Program managers are rewarded by their ability to keep their programs on schedule

and within budget; anything that detracts from these goals is unwelcome. Thus, the attractor mechanism for individual programs in an SoS development program is problematic. There is a cost to the program, but no apparent value.

Campbell (1977) argues that measures of organizational effectiveness depend on an organization's approach to effectiveness. Campbell identifies four types of approaches. The output goal approach emphasizes end results, such as profit and quality; the internal process approach emphasizes the maintenance of effective human relationships within the organization; the systems resources approach emphasizes the ability to draw needed resources, such as funding, from its environment; and the stakeholder approach recognizes the preferences of various interest groups inside and outside the organization.

Program offices are examples of organizations that fit the system resource approach model. For a program office to succeed, it must obtain the necessary funding to ensure the ongoing development of the system for which it is responsible. Thus, program offices will behave in a way that maximizes the probability of obtaining continuing funding and perhaps increased funding. Program offices will strongly resist any behavior that jeopardizes funding.

Dunlap (2011) observes that there was a critical SoS funding issue affecting SoS systems engineering in the Future Combat SoS program:

> The system engineering strategy for requirements management at the system of systems level worked effectively. The requirement teams and the leads were funded by and under the management of the system of systems engineering integration team. The system of system[s] engineering integration team could require the requirements team to work together and reach a consensus. This was not the case for the systems' prime contractors [and] the requirements lead. The individual prime item systems had independent contracts, as well as varied management structures and funding lines. The system allocation of functions and requirements were never successfully decomposed or allocated from a system of systems to subsystem[s]/component[s].

The Future Combat System started as a hierarchical architecture for decomposing and allocating functions from [the] system of systemsto [the] systems and then to [the] sub-systems. Requirements were to be allocated at each level to maximize integration and reduce unnecessary redundancy and systems. The program funding structure did not allow for the required constraints to be mandated on the systems. The Future Combat System's architecture resulted in [the] parent system [-]of[-]systems requirements with unacceptable children requirements at the system level.

A solution to advance progress in resolving the issue on a constraint being accepted at the system and system element levels of the system of systems would have been readily available. Funding could have been structured to align with a hierarchical management organizational structure.

Some program managers may agree to participate in a WBCS without additional funding, but to assure that all program managers agree to participate, funding should be made available to cover the additional, albeit small, costs of participating. Ideally, additional funding should be made to the SoS program through a contract modification, if necessary, and the SoS program office should then allocate funds to each of the individual associated programs to cover their additional costs of participating in the web-based system.

# V.	A Web-Based Collaborative System

One mechanism that holds promise for meeting many of the requirements for inter-program collaboration is a web-based collaborative system (WBCS) on which personnel from all programs associated with an SoS can input and retrieve information required to align the individual programs.

A goal in this research is to explore the feasibility of such a web-based system to facilitate the development of an SoS through collaborative behavior from the system programs that develop the individual systems constituting the SoS. The purposes of this system are to aid in effecting collaboration through management and coordination of all system programs—the SoS program and the system programs—and to provide visibility to the progress of each program, to problems encountered by each program, and to collaborative decisions made by all the programs involved. The system is, thus, used to effect a successful development of the SoS as well as all the constituent systems.

The web-based system proposed in this work is based on the concept of an architecture for distributed and interoperable management of multi-site production projects espoused in Ishak et al., (2010).   The kernel of this system is the SCEP (Supervisor, Customer, Environment, Producer) model (Archimede & Coudert, 2001).   It is based on multi-agent systems (MAS; Ferber, 1999). SCEP allows a distributed management of acquisition programs (i.e., system programs and the SoS program) and cooperation via a shared environment (e.g., blackboard) between an agent representing the SoS program and the system program agents representing the individual system programs under the control of a supervisor agent. It also provides global visibility (forecasting horizon) of all parties involved, enabling satisfaction of the SoS program objectives and those of the individual system programs. In this case, the customer is the SoS program, and the producer is a system program. Through this web-based system, the management and

coordination of the system programs and the SoS program becomes that of virtual enterprises.

Figure 9 shows the architecture of the web-based system. As in Ishak et al. (2010), the Register acts as an information broker. It discovers and publishes a system program's progress status and the need points (including progress, or lack thereof, issues, concerns, milestones, etc.) that affect the development of the SoS. These two functions—discovering and publishing—communicate with the Register DataBase (RDB) containing the information on the status of all programs. Discovery here means identifying failures to reach the need points or to meet the milestones required by development of the SoS or any of the constituent systems. Such need points and milestones are illustrated in Figures 6–8.
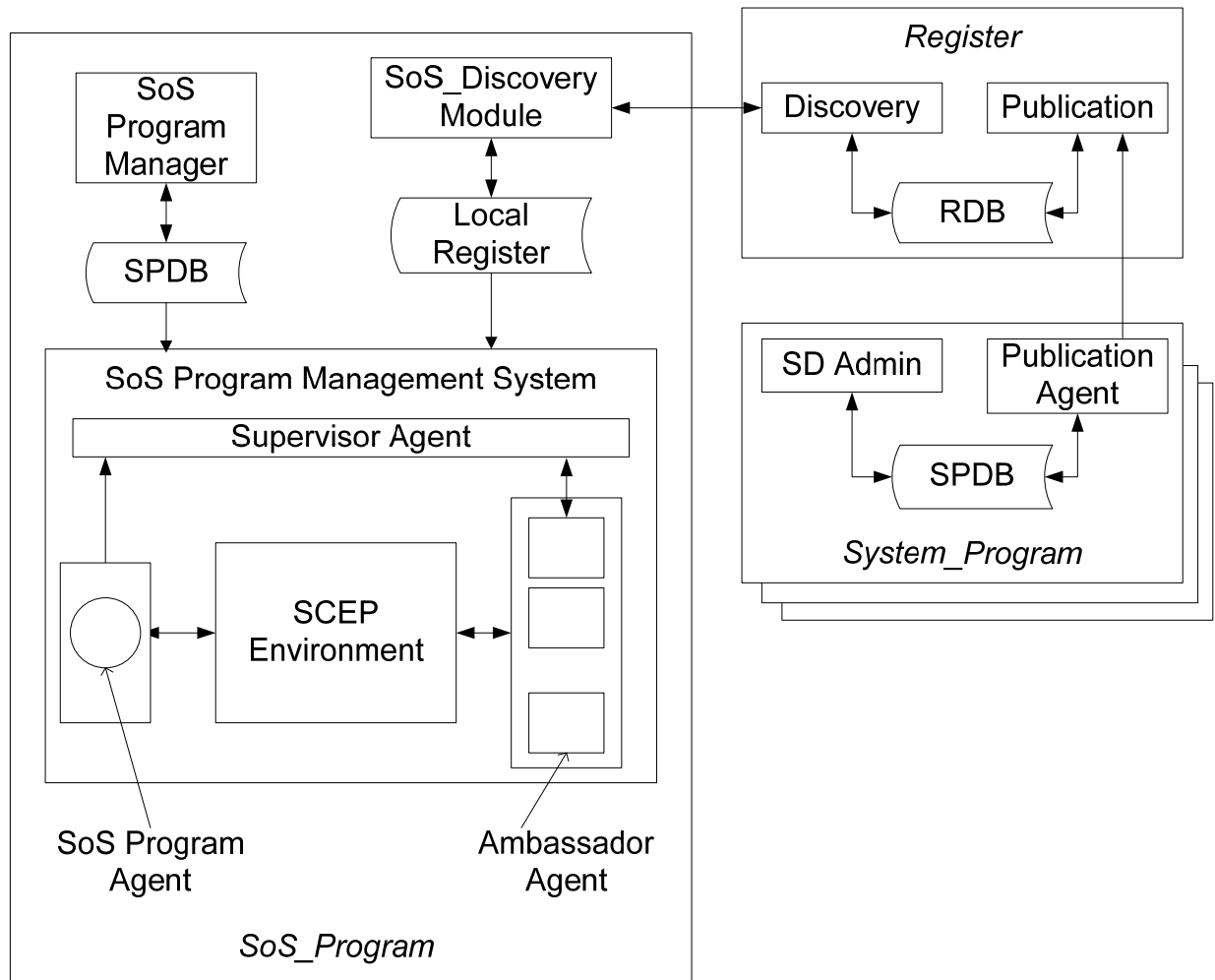
Figure 9.   Web-Based SoS Collaborative System Architecture
Note. This figure was adapted from Figure 3 in Ishak et al. (2010).

A System_Program has a system development administrator (SD Admin), which retrieves from the System Program DataBase (SPDB) all information (e.g., needs, milestones, and requirements, etc.) pertaining to the SoS development. It also stores in the SPDB the outcomes of the SP program's activities in relation to the SoS programs. A "publication agent" publishes the status of the system program (i.e., need points or milestones) through its interaction with the Register.

The SoS_Program has the following components — the SoS Program Manager, the SoS Program DataBase (SoSPDB), the SoS Program Management

System, an SoS_Discovery module, and the Local Register. The SoS Program Manager is responsible for the SoS program realization. The SoSPDB contains the description of the SoS program, the status of the system programs, a local register, and the program management system. The SoS_Discovery module obtains from the Register the status of all system programs and stores it at the Local Register. A limited copy of the Register, the Local Register stores information about the system's registered concerns and progress. It accelerates the discovery of issues and aids the SoS program in managing the system programs.

To enhance the collaboration between the SoS program and the system programs, the information in the Local Register and the Register must be synchronized and verified for aging and accuracy. The SoS Program Management System allows for distributed management of the collaboration of the SoS program with the system programs. The SCEP supervisor agent obtains details of the SoS program from the SPDB. It also creates the shared environment, the SoS program agent representing the SoS program, and the SCEP ambassador agents representing the system programs. As elaborated in Ishak et al. (2010), the agents of the SCEP model are integrated into the SoS Program Management System so as to manage the execution of the system programs in a distributed and autonomous manner. Through the shared SCEP environment, the management of the programs is effected by cooperation between the SoS program agent and the ambassador agents in resolving any issues and concerns from the system programs.

The first step of the management process involves the identification of a system program that has concerns and whose status has been published and discovered. The second step deals with instantiation of SCEP components on the SoS_Program side and connection to the System_Program identifed in the first step. The SCEP supervisor agent creates the shared environment as well as the SoS program and ambassador agents. The last step concerns interactions and cooperation between the SoS_Program and its System_Programs through the SCEP instantiation.

At the beginning of the SoS program, through the supervisor agent, the SoS program agent deposits the SoS program requirements in the SCEP environment. Invited by the supervisor agent, every ambassador agent pulls from the environment the SoS requirements and constraints on the individual system program it represents. After the collection of information, the ambassador agent generates the requirements for the corresponding system. The ambassador agent receives the status and concerns from the corresponding system program and deposits them in the SCEP environment to be discovered by the SoS program agent and other ambassador agents. The lack of progress of each system program will, thus, be visible to all parties, and timely corrective actions can then be taken.

Furthermore, as this architecture might underlie commercially available tools, this work does not suggest that a new software tool be developed to implement this architecture. This architecture might be used as a guide to aid in identifying any of the commercially available tools for use in effecting collaboration among the programs in an SoS development effort.

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VI.   Enabling Contracting Structures

As discussed earlier in this report, a lack of alignment and a lack of collaboration between and among the individual system programs are two important issues leading to problems in SoS acquisition, and a web-based SoS collaborative system can be developed to support DoD SoS acquisition programs. This section now presents how contracting structures, more specifically, contract management processes, can facilitate the use of the web-based SoS collaborative system by the SoS individual system programs. The context of the contract management process is used to illustrate these structures.

Typically, the contract management process is discussed from two perspectives—the pre-contract award phase and the post-contract award phase. However, to provide additional granularity and a deeper level of analysis, it is appropriate to discuss the process using a six-phase life cycle.   These six phases of contract management for the procuring organization consist of Procurement Planning, Solicitation Planning, Solicitation, Source Selection, Contract Administration, and Contract Closeout (Rendon & Snider, 2008). Each of these contract management life cycle phases involves specific contracting activities that can facilitate the use of a web-based collaboration system. Given the SoS context of this research, these contract management activities would be performed by any one of the individual system program offices.

Procurement Planning involves the process of identifying which business needs can best be met by procuring products or services outside the organization. This process involves determining whether to procure, how to procure, what to procure, how much to procure, and when to procure (Rendon & Snider, 2008). This phase of the contracting process includes

- conducting outsource analysis;

- determining and defining the requirement (the supply or service to procure);

- conducting market research and/or a pre-solicitation conference;

- developing preliminary requirements documents such as work breakdown structures (WBS), statements of work (SOW), performance work statement (PWS), or other descriptions of the supply or service to be procured;

- developing preliminary budgets and cost estimates;

- preliminarily considering contract type and any special contract terms and conditions; and

- conducting a risk analysis.

The procurement planning activities for each individual system program must be collaborated on and aligned with the acquisition objectives of the SoS acquisition program. Specific activities such as defining the requirement, developing contract statements of work, determining system specifications, and conducting a risk analysis should be performed in collaboration and alignment with the other acquisition programs within the SoS program. The use of a web-based collaboration system accessible by the SoS program and individual system programs would facilitate this collaboration and alignment.

Solicitation Planning involves the process of preparing the documents needed to support the solicitation. This process involves documenting program requirements and identifying potential sources (Rendon & Snider, 2008). This process includes

- determining procurement method (sealed bids, negotiated proposals, e-procurement methods, procurement cards, etc.);

- determining contract type (fixed-price versus cost type);

- developing the solicitation document (IFB, RFQ, or RFP);

- determining proposal evaluation criteria and contract-award strategy;

- structuring contract terms and conditions; and

- finalizing the solicitation, WBS, SOW, and product or service descriptions.

The above solicitation planning activities reflect the results of the procurement planning process. As the system-of-systems program office begins developing the solicitation documents (for example, the WBS, SOW, specifications, etc.), collaboration and alignment with the other acquisition program offices making up the system of systems take on an increased importance. The use of a web-based collaboration system accessible by the SoS and individual system programs would facilitate this much-needed collaboration and alignment.

Once the solicitation (for example, the Request for Proposal) is completed, the Solicitation phase is the process of issuing or deploying the solicitation and obtaining information bids or proposals from the offerors on how project needs can be met (Rendon & Snider, 2008). This process includes

- conducting advertising of the procurement opportunity, or providing notice to interested offerors;
- conducting a pre-proposal conference, if required; and
- developing and maintaining a qualified bidders list.

For the Solicitation process, many government agencies have established web-based systems for centralizing and providing the maximum visibility for the advertisement of procurement opportunities to industry. This ensures a level of integrity, accountability, and transparency in the contracting process. For the United States, federal government contracting opportunities are publicized through the Government Point of Entry (GPE), which is the single point where government business opportunities greater than $25,000, including synopses of proposed contract actions, solicitations, and associated information, can be accessed electronically by interested offerors (www.fedbizopps.gov).

Source Selection is the process of receiving bids or proposals and applying the proposal evaluation criteria to select a supplier (Rendon & Snider, 2008). The source selection process includes the evaluation of offers and proposals, and contract negotiations between the buyer and the seller in attempting to come to agreement on all aspects of the contract, including cost, schedule, performance, terms and conditions, and anything else related to the contracted effort. This process includes

- applying evaluation criteria to management, cost, and technical bids or proposals;
- negotiating with suppliers; and
- executing the contract award strategy.

The complexity of the source selection process will depend on the contract award strategy selected. The complexity and challenges of the contract source selection process will depend on whether the government uses a price-directed award strategy (for example, lowest price/technically acceptable) or a trade-off process (for example, technical approach is more important than price).. In some contract source selections, in which the requirement is clearly definable and the risk of unsuccessful contract performance is minimal, cost or price may play a dominant role. In other source selections, in which the requirement is less definitive and more development work is required (resulting in greater performance risk), more technical or past performance considerations may play a dominant role.

If the individual system program requirement (supply or service being procured) will have a significant impact on the SoS acquisition program, it will be essential for the other programs to be involved in the source selection process, especially the evaluation of offeror cost, schedule, and technical proposals, as well as past performance evaluation. The use of a web-enabled collaboration system will facilitate the required integrated assessment of offeror capabilities identified during this process.

Once the contract is awarded, the contract administration phase begins. Contract administration is the process of ensuring that each party's performance meets the contractual requirements (Rendon & Snider, 2008). The activities involved in contract administration will depend on the contract statement of work, contract type, and contract performance period. The contract administration process typically includes

- conducting a pre-performance conference,
- monitoring the contractor's work results,
- measuring the contractor's performance, and
- managing the contract change-control process.

In major defense acquisition projects, such as SoS acquisition programs, the contract administration phase is critical to effective project management. In this phase of the contract management process, the contractor is performing the statement of work requirements, and the completed work is then measured and evaluated by the buying organization.

A significant aspect of the contract administration phase consists of monitoring the contractor's performance. The monitoring and controlling project management processes are focused on ensuring that project objectives are met as the project manager performs such activities as measuring progress against plan, holding status meetings, and correcting the divergences from schedule or budget. Another major emphasis of contract administration activities is measuring contractor performance. The contractor's performance is measured to ensure that the actual contractor work results meet the cost, schedule, and performance standards agreed to in the contract. In addition, it would be naive to think that once the contract is awarded, the contract will never need to be changed or modified during the contract period. Contracts frequently require changes due to various reasons during the period of performance. Another major part of contract administration activities is focused on managing the contract-changes process.

Once again, in the SoS context, given the high risk and complexities of SoS acquisition programs, it will be essential for the other program offices to be involved in the contract administration process, especially the monitoring, controlling, and measuring of the contractor's performance, as well as the coordination, review, and approval of contract changes. The use of a web-enabled collaboration system will facilitate the required integrated administration of the SoS contracts.

Typically, an acquisition contract can end in one of three ways: First, the contract can be successfully completed and allowed to run its full period of performance, and then closed out; second, the contract can be terminated for the convenience of the government; or third, the contract can be terminated for default. Regardless of how the contract ends, in the end, all contracts must be closed out. Thus, the final phase of the contracting process is the Contract Closeout/Termination phase. Contract Closeout is the process of verifying that all administrative matters are concluded on a contract that is otherwise physically complete (Rendon & Snider, 2008). The closeout of contracts that are physically complete requires the verification of documentation that reflects the completion of all required contractual actions. A contract is considered to be physically completed when the contractor has completed the required deliveries and the government has inspected and accepted the supplies; the contractor has performed all services, and the government has accepted the services; and all contract option provisions have expired.

This contract closeout process includes the following activities:

- final inspection and acceptance of products or services,
- processing of government property dispositions,
- final contractor payments, and
- documentation of the contractor's final past-performance report.

The contract closeout process for each individual system program must be collaborated on and aligned with the acquisition objectives of the SoS acquisition program. In the SoS context, specific activities, such as final inspection and acceptance of products or services, should be performed in collaboration and alignment with the other acquisition programs within the SoS. Once again, the use of a web-based collaboration system accessible by the SoS and individual system program offices would facilitate this collaboration and alignment.

The contract management process is a critical aspect of a system acquisition program. It is typically the effectiveness of the contracting process that determines the success of an acquisition program. SoS acquisition programs entail a higher level of complexity and risk, which necessitates the need for collaboration and alignment among the individual system programs. The use of the web-based SoS collaborative system by the SoS individual system programs can facilitate this collaboration and alignment.

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VII.   Conclusion

System-of-systems (SoS) acquisition research has identified lack of alignment and lack of collaboration as two important issues leading to problems in SoS acquisition. This report captures the exploratory work toward improving alignment between and collaboration among the individual system programs in the development of an SoS.

An SoS inter-program collaboration approach is proposed. It is inspired by some existing web-based collaborative systems, such as eBay, Facebook, and Eureka, and suggests an attraction mechanism to effect SoS inter-program collaboration. In addition, a web-based collaborative system is also suggested. Based on an architecture for distributed and interoperable management of multi-site production projects, it allows personnel of all programs associated with an SoS to input need points for component system inputs and retrieve information required to align the individual programs. This architecture might be used as a guide to aid in identifying any of the commercially available tools for use in effecting collaboration among the programs in an SoS development effort.

Furthermore, as part of this SoS inter-program collaboration approach, contracting structures for facilitating collaboration among the system programs are also considered.

Finally, this work forms a basis for implementing a web-based SoS collaborative system to support DoD SoS acquisition programs.

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