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Flexible and Intelligent Learning Architectures for SoS (FILA-SoS)

Volume 1 – Integrated Model Structure

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EXECUTIVE SUMMARY

Multi-faceted systems of the future will entail complex logic and reasoning with many levels of reasoning in intricate arrangement. The organization of these systems involves a web of connections and demonstrates self-driven adaptability. They are designed for autonomy and may exhibit emergent behavior that can be visualized. Our quest continues to handle complexities, design and operate these systems. The challenge in Complex Adaptive Systems design is to design an organized complexity that will allow a system to achieve its goals. This report attempts to push the boundaries of research in complexity, by identifying challenges and opportunities. Complex adaptive system-of-systems (CASoS) approach is developed to handle this huge uncertainty in socio-technical systems.

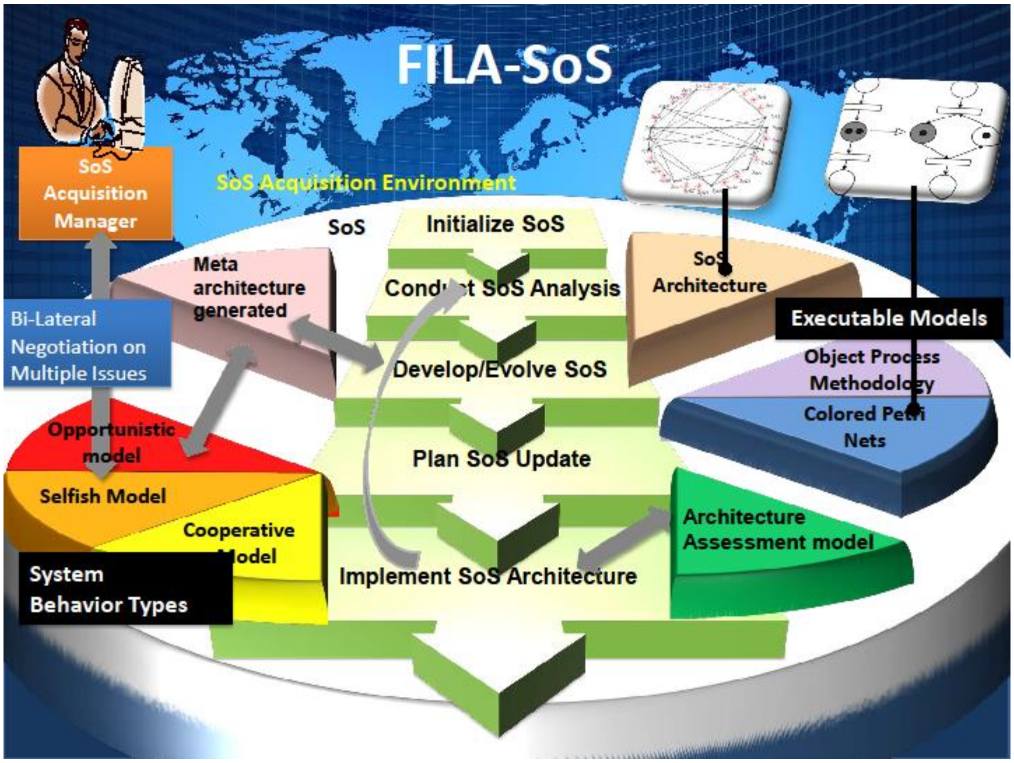
Although classically (Dahmann, Rebovich, Lowry, Lane, & Baldwin, 2011) four categories of SoS are described in literature namely; Directed, Collaborated, Acknowledged and Virtual. However, there exist infinitely many SoS on the edges of these categories thus making it a continuum. Many SoS with different configurations can fill this gap. These four types of SoS vary based on their degree of managerial control over the participating systems and their structural complexity. The spectrum of SoS ranges from Directed SoS that represents complicated systems to Virtual SoS that are complex systems.

Acknowledged SoS lie in between this spectrum. This particular SoS is the focal point of our research endeavor. Acknowledged SoS and Directed SoS share some similarities such as both have (Dahman & Baldwin, 2011) SoS objectives, management, funding and authority. Nevertheless, unlike Directed SoS, Acknowledged SoS systems are not subordinated to SoS. However, Acknowledged SoS systems retain their own management, funding and authority in parallel with the SoS. Collaborative SoS are similar to Acknowledged SoS systems in the fact that systems voluntarily work together to address shared or common interest.

Flexible and Intelligent Learning Architectures for SoS (FILA-SoS) integrated model is developed in this research task provides a decision making aid for SoS manager based on the wave model. The model developed called the FILA-SoS does so using straightforward system definitions methodology and an efficient analysis framework that supports the exploration and understanding of the key trade-offs and requirements by a wide range system-of-system stakeholders and decision makers in a short time. FILA-SoS and the Wave Process address four of the most challenging aspects of system-of-system architecting:

1. Dealing with the uncertainty and variability of the capabilities and availability of potential component systems
2. Providing for the evolution of the system-of-system needs, resources and environment over time
3. Accounting for the differing approaches and motivations of the autonomous component system managers
4. Optimizing system-of-systems characteristics in an uncertain and dynamic environment with fixed budget and resources

Some of the highlights of FILA-SoS are listed in terms of its capabilities, value added to systems engineering, ability to perform "What-if Analysis", modularity of integrated models, its potential applications in the real world and future additions to the current version.



FILA-SoS has a number of unique capabilities such as integrated model for modeling and simulating SoS systems with evolution for multiple waves. It also has modularity in the structure where the models can be run independently and in conjunction with each other. Besides there are a couple of different models for both architecture generation and SoS behavior and various individual system behavior negotiation models between SoS and individual systems. In terms of value added FILA-SoS aids the SoS manager in future decision making. It also helps in understanding the emergent behavior of systems in the acquisition environment and impact on SoS architecture quality. FILA-SoS serves as an artifact to study the dynamic behavior of different type of systems (non-cooperative, semi-cooperative, cooperative). It enables us to identify intra and interdependencies among SoS elements and the acquisition environment. FILA-SoS can provide a "What-if" Analysis depending on variables such as SoS funding and capability priority that can be changed as the acquisition progresses through wave cycles. It has the ability to simulate any architecture through colored petri nets. In addition, it can simulate rules of engagement & behavior settings: all systems are non-cooperative, all systems are semi-cooperative, and all systems are cooperative or a combination. Some of the potential applications include modeling a wide variety of complex systems models such as logistics, and cyber-physical systems. It also acts as a test-bed for decision makers to evaluate operational guidelines and principles for managing various acquisition environment scenarios. Future Capabilities that are currently in progress are extending the model to include multiple interface alternatives among systems and incorporation of risk models into environmental scenarios.

Integrated Model Structure for FILA-SoS Version 1.0 is described. It provides a short description of all independent models that make up the FILA-SoS integrated model and reports the workings of the model with three notional System-of-Systems namely; Toy Problem for aircraft carrier performance assessment, ISR (intelligence surveillance and reconnaissance) and SAR (search and rescue).

The project reports span 17 volumes. Each report describes the various aspects of the FILA-SOS integrated model:

Volume 1: Integrated Model Structure
Volume 1 is the Integrated Model Structure report for FILA-SoS Version 1.0. It provides a short description of all independent models that make up the FILA-SoS integrated model. Integrated FILA-SoS developed is tested in three notional System-of-Systems namely; Toy Problem for Aircraft Carrier Performance Assessment, ISR (intelligence surveillance and reconnaissance) and SAR (search and rescue). FILA-SoS integrated model is currently being validated with a real life data from a medium sized SoS. The results of this validation are given in volume 17.

Volume 2: Meta-Architecture Generation Multi-Level Model
Volume 2 describes Meta-Architecture Generation Multi-Level Model. The multi-level meta-architecture generation model considers constructing an SoS architecture such that each capability is provided by at least one system in the SoS and the systems in the SoS are able to communicate with each other. Secondly, it has multiple objectives for generating a set of SoS architectures namely; maximum total performance, minimum total costs and minimum deadline. Finally, the model establishes initial contracts with systems to improve performances.

Volume 3: Fuzzy-Genetic Optimization Model
Volume 3 illustrates the second meta-architecture generation model known as the Fuzzy-Genetic optimization model. This model is based on evolutionary multi-objective optimization for SoS architecting using genetic algorithms and four key performance attributes (KPA) as the objective functions. It also has a type-1 fuzzy assessor for dynamic assessment of domain inputs and that forms the fitness function for the genetic algorithm. It returns the best architecture (meta-architecture) consisting of systems and their interfaces. It is a generalized method with application to multiple domains such as Gulf War Intelligence/Surveillance/Reconnaissance Case, Aircraft Carrier Performance Assessment Case and Alaskan Maritime Search and Rescue Case.

Volume 4: Architecture Assessment Model
Volume 4 describes an Architecture Assessment Mode that can capture the non-linearity in key performance attribute (KPA) tradeoffs, is able to accommodate any number of attributes for a selected SoS capability, and incorporate multiple stakeholder's understanding of KPA's. Assessment is based on a given meta-architecture alternative. This is done using type-1 fuzzy sets and fuzzy inference engine. The model provides numerical values for meta-architecture quality.

Volume 5: Cooperative System Negotiation Model
Volume 5 specifically describes the Cooperative System Negotiation Model. The systems following this model behave cooperatively while negotiating with the SoS manager. The model

of cooperative behavior is based on agent preferences and the negotiation length. Each system agent has two inherent behaviors of cooperativeness: Purposive (normal behavior) and Contingent (behavior driven by unforeseen circumstances). The approach models the tradeoff between the two behaviors for the systems. A fuzzy weighted average approach is used to arrive at the final proposed value.

Volume 6: Non-Cooperative System Negotiation Model

Volume 6 goes on to describe the Non-Cooperative System Negotiation Model in which systems behave in their self-interest while negotiating with the SoS coordinator. A mathematical model of individual system's participation capability and self-interest negotiation behavior is created. This methodology is an optimization-based generator of alternatives for strategically negotiating multiple items with multiple criteria. Besides, a conflict evaluation function that estimates prospective outcome for identified alternative is proposed.

Volume 7: Semi-Cooperative System Negotiation Model

Volume 7 describes the third and last system negotiation model, which illustrates the Semi-Cooperative System Negotiation Model. It exhibits the capability of being flexible or opportunistic: i.e., extremely cooperative or uncooperative based on different parameter values settings. A Markov-chain based model designed for handling uncertainty in negotiation modeling in an SoS. A model based on Markov chains is used for estimating the outputs. The work assigned by the SoS to the system is assumed to be a ``project'' that takes a random amount of time and a random amount of resources (funding) to complete.

Volume 8: Incentive based Negotiation Model for System of Systems

Volume 8 explains the SoS negotiation model also called the Incentive Based Negotiation Model for System of Systems. This model is based on two key assumptions that are to design a contract to convince the individual systems to join the SoS development and motivate individual systems to do their tasks well. Game theory and incentive based contracts are used in the negotiation model that will maximize the welfare for parties involved in the negotiation. SoS utility function takes into account local objectives for the individual systems as well as global SoS objective whereas the incentive contract design persuades uncooperative systems to join the SoS development.

Volume 9: Model for Building Executable Architecture

Volume 9 illustrates the process of building Executable Architectures for SoS. The operations of the SoS is a dynamic process with participating system interacting with each other and exchange various kinds of resources, which can be abstract information or physical objects. This is done through a hybrid structure of OPM (Object process methodology) and CPN (Colored petri nets) modeling languages. The OPM model is intuitive and easy to understand. However, it does not support simulation, which is required for accessing the behavior related performance. This is achieved by mapping OPM to CPN, which is an executable simulation language. The proposed method can model the interactions between components of a system or subsystems in SoS. In addition, it can capture the dynamic aspect of the SoS and simulate the behavior of the SoS. Finally, it can access various behavior related performance of the SoS and access different constitutions or configurations of the SoS which cannot be incorporated into the meta-architecture generation models of Volume 2 & 3.

Volume 10: Integrated Model Software Architecture and Demonstration FILA-SoS Version 1.0
Volume 10 elucidates the Integrated Model Software Architecture and Demonstration based on the models described above. Volume 11 and thereon the reports are aimed at the upcoming newer version 2.0 of FILA-SoS.

Volume 11: Integrated Model Structure FILA-SoS Version 2.0
Volume 11 provides Integrated Model Structure for FILA-SoS Version 2.0 that could be implemented in a new software environment.

Volume 12: Complex Adaptive System-of-System Architecture Evolution Strategy Model for FILA-SoS Version 2.0
Volume 12 provides a model to answer the first research question "What is the impact of different constituent system perspectives regarding participating in the SoS on the overall mission effectiveness of the SoS?" It is named the Complex Adaptive System-of-System Architecture Evolution Strategy Model and is incorporated in FILA-SoS Version 2.0. This volume describes a computational intelligence based strategy involving meta-architecture generation through evolutionary algorithms, meta-architecture assessment through type-2 fuzzy nets and finally its implementation through an adaptive negotiation strategy.

Volume 13: On the Flexibility of Systems in System of Systems Architecting: A new Meta-Architecture Generation Model for FILA-SoS Version 2.0
Volume 13 is termed the Flexibility of Systems in System of Systems Architecting: A new Meta-Architecture Generation Model for FILA-SoS Version 2.0. The research question is answered through an alternative technique to meta-architecture generation besides the one described in Volume 2.

Volume 14: Assessing the Impact on SoS Architecture Different Level of Cooperativeness: A new Model for FILA-SoS Version 2.0
Volume 14 proposes a new method for Assessing the Impact on SoS Architecture Different Level of Cooperativeness. Second research question is answered through a model that allows different levels of cooperativeness of individual systems.

Volume 15: Incentivizing Systems to Participate in SoS and Assess the Impacts of Incentives: A new Model for FILA-SoS Version 2.0
Volume 15 is an extension of previous systems negotiation models based on incentivizing and is aptly called Incentivizing Systems to Participate in SoS and Assess the Impacts of Incentives: A new Model for FILA-SoS Version 2.0. It also provides an approach to answer the third research question "How should decision-makers incentivize systems to participate in SoS, and better understand the impact of these incentives during SoS development and effectiveness?". This model is based on the fact that providing incentives only depending on the outcome may not be enough to attract the attention of the constituent systems to participate in SoS mission. Therefore, this model extends the approach as described in Volume 8 while considering the

uncertainty in the acquisition environment. The incentive contract is designed based on the objectives of the SoS and the individual systems. Individual system's objective is to secure highest incentives with minimal effort while the SoS manager's goal is to convince individual systems to join the SoS development while maximizing its own utility.

Volume 16: Integrated Model Software Architecture for FILA-SoS Version 2.0
Volume 16 gives an overview of the integrated model architecture in version 2.0 of the software. It includes all old and new models previously mentioned.

Volume 17: FILA-SoS Version 1.0 Validation with Real Data
Volume 17 describes the validation of the FILA-SoS Version 1.0 with a real life data provided by MITRE Corporation by from a moderately sized SoS.

INTRODUCTION

MOTIVATION FOR RESEARCH

In the real world, systems are complex, non-deterministic, evolving, and have human centric capabilities. The connections of all complex systems are non-linear, globally distributed, and evolve both in space and in time. Because of non-linear properties, system connections create an emergent behavior. It is imperative to develop an approach to deal with such complex large-scale systems. The approach and goal is not to try and control the system, but design the system such that it controls and adapts itself to the environment quickly, robustly, and dynamically. These complex entities include both socioeconomic and physical systems, which undergo dynamic and rapid changes. Some of the examples include transportation, health, energy, cyber physical systems, economic institutions and communication infrastructures.

In addition, the idea of "System-of-Systems" is an emerging and important multidisciplinary area. An SoS is defined as a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities greater than the sum of the capabilities of the constituent parts. Either of the systems alone cannot independently achieve the overall goal. System-of- Systems (SoS) consists of multiple complex adaptive systems that behave autonomously but cooperatively (Dahman, Lane, Rebovich, & Baldwin, 2008). The continuous interaction between them and the interdependencies produces emergent properties that cannot be fully accounted for by the "normal" systems engineering practices and tools. System of Systems Engineering (SoSE), an emerging discipline in systems engineering is attempting to form an original methodology for SoS problems (Luzeaux, 2013).

Since SoS grow in complexity and scale with the passage of time it requires architectures that will be necessary for understanding and governance and for proper management and control. Systems architecting can be defined as specifying the structure and behavior of an envisioned system. Classical system architecting deals with static systems whereas the processes of System of Systems (SoS) architecting has to be first done at a meta-level. The architecture achieved at a meta-level is known as the meta-architecture. The meta-architecture sets the tone of the architectural focus (Malan & Bredemeyer, 2001). It narrows the scope of the fairly large domain space and boundary. Although the architecture is still not fixed but meta-architecture provides multiple alternatives for the final architecture. Thus architecting can be referred to as filtering the meta-architectures to finally arrive at the architecture. The SoS architecting involves multiple systems architectures to be integrated to produce an overall large scale system meta-architecture for a specifically designated mission (Dagli & Ergin, 2008). SoS achieves the required goal by introducing collaboration between existing system capabilities that are required in creating a larger capability based on the meta-architecture selected for SoS. The level of the degree of influence on individual systems architecture through the guidance of SoS manager in implementing SoS meta-architecture can be classified as directed, acknowledged, collaborative and virtual. Acknowledged SoS have documented objectives, an elected manager and defined resources for the SoS. Nonetheless, the constituent systems retain their independent ownership, objectives, capital, development, and sustainment approaches. Acknowledged SoS shares some similarities with directed SoS and collaborative SoS. There are four types of SoS that are described below:

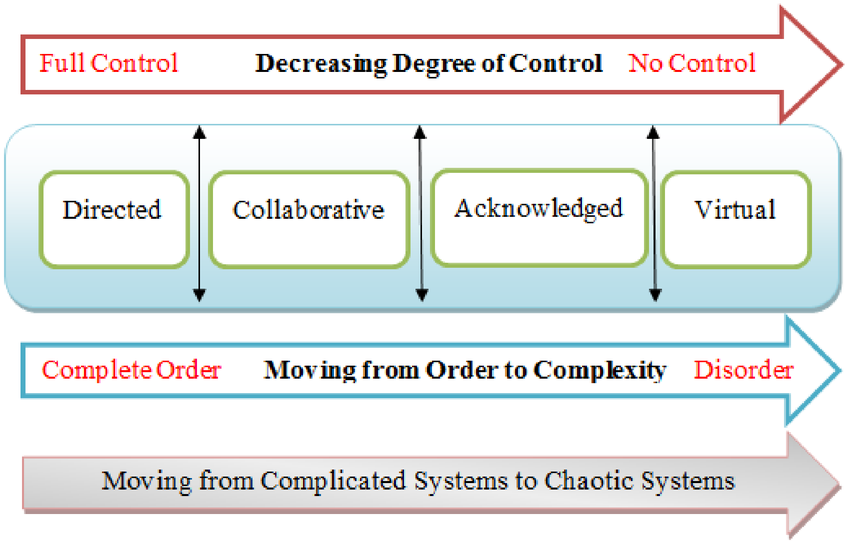


Figure 1 Schematic Drawing of Four Classical Types of SoS Based on Degree of Control and Degree of Complexity

Virtual

- Virtual SoS lack a central management authority and a centrally agreed upon purpose for the system-of-systems.
- Large-scale behavior emerges—and may be desirable—but this type of SoS must rely upon relatively invisible mechanisms to maintain it.

Collaborative

- In collaborative SoS the component systems interact more or less voluntarily to fulfill agreed upon central purposes.

Acknowledged (*FILA-SoS integrated model is based on Acknowledged SoS*)

- Acknowledged SoS have recognized objectives, a designated manager, and resources for the SoS; however, the constituent systems retain their independent ownership, objectives, funding, and development and sustainment approaches.
- Changes in the systems are based on collaboration between the SoS and the system.

Directed

- Directed SoS's are those in which the integrated system-of-systems is built and managed to fulfill specific purposes.
- It is centrally managed during long-term operation to continue to fulfill those purposes as well as any new ones the system owners might wish to address.
- The component systems maintain an ability to operate independently, but their normal operational mode is subordinated to the central managed purpose.

This research is based on Acknowledged SoS. The major objectives of the reasearch are:

- To develop a simulation for Acknowledged SoS architecture selection and evolution.
- To have a structured, repeatable approach for planning and modeling.
- To study and evaluate the impact of individual system behavior on SoS capability and architecture evolution process.

The dynamic planning for a SoS is a challenging endeavor. Department of Defense (DoD) programs constantly face challenges to incorporate new systems and upgrade existing systems over a period of time under threats, constrained budget, and uncertainty. It is therefore necessary for the DoD to be able to look at the future scenarios and critically assess the impact of technology and stakeholder changes. The DoD currently is looking for options that signify affordable acquisition selections and lessen the cycle time for early acquisition and new technology addition. FILA-SoS provides a decision aid in answering some of the questions.

This volume gives an overview of a novel methodology known as the Flexible Intelligent & Learning Architectures in System-of-Systems (FILA-SoS). Some the challenges that are prevalent in SoS architecting and how FILA-SoS attempts to address them is explained in the next section.

SYSTEM OF SYSTEM CHALLENGES

All these recent developments are helping us to understand Complex Adaptive Systems. They are at the edge of chaos as they maintain dynamic stability through constant self-adjustment and evolution. Chaos and order are two complementary states of our world. A dynamic balance exists between these two states.

Order and structure are vital to life. Order ensures consistency and predictability and makes the creation of systems possible. However, too much order leads to rigidity and suppresses creativity. Chaos constantly changes the environment creating disorder and instability but can also lead to emergent behavior and allows novelty and creativity. Thus, sufficient order is necessary for a system to maintain an ongoing identity, along with enough chaos to ensure growth and development. The challenge in Complex Adaptive Systems design is to design an organized complexity that will allow a system to achieve its goals. SoS is a complex systems by its nature due to the following characteristics that are component systems are operationally independent elements and also managerially independent of each other. This means that component systems preserve existing operations independent of the SoS. SoS has an evolutionary development and due to the large scale complex structure shows an emergent behavior. Emergence means the SoS performs functions that do not reside in any one component system.

2012 INCOSE SoS working group survey identified seven ‘pain points’ raising a set of questions for systems engineering of SoS which are listed in Table 1 (Dahman, 2012).

Table 1 System of Systems and Enterprise Architecture Activity

Pain Points	Question
Lack of SoS Authorities & Funding	What are effective collaboration patterns in systems of systems?
Leadership	What are the roles and characteristics of effective SoS leadership?
Constituent Systems	What are effective approaches to integrating constituent systems into a SoS?
Capabilities & Requirements	How can SE address SoS capabilities and requirements?
Autonomy, Interdependencies & Emergence	How can SE provide methods and tools for addressing the complexities of SoS interdependencies and emergent behaviors?
Testing, Validation & Learning	How can SE approach the challenges of SoS testing, including incremental validation and continuous learning in SoS?
SoS Principles	What are the key SoS thinking principles, skills and supporting examples?

The importance and impact on systems engineering of each pain point is illustrated below:

- **Lack of SoS Authorities & Funding and Leadership** pose several and severe governance and management issues for SoS. This conditions has a large impact on the ability to implement systems engineering (SE) in the classical sense to SoS. In addition, this problem affects the modeling & simulation activities.
- **Constituent Systems** play a very important role in the SoS. As explained earlier usually they have different interests and ambitions to achieve, which may or may not be aligned with the SoS.. Similarly models, simulations and data for these systems will naturally have to be attuned to the specific needs of the systems, and may not lend themselves easily to supporting SoS analysis or engineering
- **Autonomy, Interdependencies & Emergence** is ramifications of the varied behaviors and interdependencies of the constituent systems making it complex adaptive systems. Emergence comes naturally in such a state, which is often unpredictable. While modeling & simulation can aid in representing and measuring these complexities, it is often hard to achieve real life emergence. This is due to limited understanding of the issues that can bring up serious consequences during validation.
- **Capability of the SoS** and the individual systems capability needs may be high level and need definition in order to align them with the requirements of the SoS mission. The SoS mission is supported by constituent systems, which may not be able (or willing) to address them.
- **Testing, Validation & Learning** becomes difficult since the constituent systems continuously keep evolving, adapting, as does the SoS environment which includes stakeholders, governments, etc. Therefore creating a practical test-bed for simulating the large dynamic SoS is a challenge in itself. Again modeling & simulation can solve part of the problem such as enhancing live test and addressing risk in SoS when testing is not feasible; however, this requires a crystal clear representation of the SoS which can be difficult as discussed in earlier points.

- **SoS Principles** are still being understood and implemented. Therefore, the rate of success is yet to be addressed formally. This poses some pressure on the progress of SoS engineering. Similarly, there is an absence of a well-established agreeable space of SoS principles to drive development and knowledge. This constricts the effective use of potentially powerful tools.

The DoD 5000.2 is currently used as the acquisition process for complex systems. Schwartz (2010) described this process as an extremely complex systemic process that cannot always constantly produce systems with expected either cost or performance potentials. The acquisition in DoD is an SoS problem that involves architecting, placement, evolution, sustainment, and discarding of systems obtained from a supplier or producer. Numerous attempts undertaken to modify and reform the acquisition process have found this problem difficult to tackle because the models have failed to keep pace with actual operational scenarios. Dombkins (1996) offered a novel approach to model complex projects as waves. He suggested that there exists a major difference in managing and modeling traditional projects versus complex projects. He further illustrated his idea through a wave planning model that exhibits a linear trend on a time scale; on a spatial scale, it tries to capture the non-linearity and recursiveness of the processes. In general, the wave model is a developmental approach that is similar to periodic waves. A period, or multiple periods, can span a strategic planning time. The instances within the periods represent the process updates. A recently proposed idea (Dahman, Lane, Rebovich, & Baldwin, 2008) that SoS architecture development for the DoD acquisition process can be anticipated to follow a wave model process. According to Dahman DoD 5000.2 may not be applicable to the SoS acquisition process. Acheson (2013) proposed that Acknowledged SoS be modeled with an Object-Oriented Systems Approach (OOSA). Acheson also proposes that for the development of SoS, the objects should be expressed in the form of a agent based model.

The environment and the systems are continuously changing. Let there be an initial environment model, which represents the SoS acquisition environment. As the SoS acquisition progresses through, these variables are updated by the SoS Acquisition Manager to reflect current acquisition environment. Thus, the new environment model at a new time has different demands. To fulfill the demands of the mission a methodology is needed to assess the overall performance of the SoS in this dynamic situation. The motivation of evolution are the changes in the SoS environment (Chattopadhyay, Ross, & Rhodes, 2008). The environmental changes consist of:

- SoS Stakeholder Preferences for key performance attributes
- Interoperability conditions between new and legacy systems
- Additional mission responsibilities to be accommodated
- Evolution of individual systems within the SoS

Evaluation of architectures is another SoS challenge area as it lends itself to a fuzzy approach because the criteria are frequently non-quantitative, or subjective (Pape & Dagli, 2013), or based on difficult to define or even unpredictable future conditions, such as “robustness.” Individual attributes may not have a clearly defined, mathematically precise, linear functional form from worst to best. The goodness of one attribute may or may not offset the badness of another attribute. Several moderately good attributes coupled with one very poor attribute may be better than an architecture with all marginally good attributes, or vice-versa. A fuzzy approach allows many of these considerations to be handled using a reasonably simple set of rules, as well as having the ability to include non-linear characteristics in the fitness measure. The simple rule set allows small adjustments to be made to the model to see how seemingly small changes affect the outcome. The methodology outlined in this research and technical report falls under a multi-level plug-and-play type of modeling approach to address various aspects of SoS acquisition environment: SoS architecture evaluation, SoS architecture evolution, and SoS acquisition process dynamics including behavioral aspects of constituent systems.

HOW DOES FILA-SOS ADDRESS SOS PAIN POINTS

The first pain point is Lack of SoS Authorities & Funding which begs a question “What are effective collaboration patterns in systems of systems?”

Since there is lack of SoS Authority but more so persuasion involved in the workings of a SoS, systems are allowed to negotiate with the SoS manager. Deadline for preparation, funding and performance required to complete the mission are some of the issues that form the negotiation protocol. Besides different combination of behavior types assigned to the systems can help us gauge the best effective collaboration patterns in systems of systems after the end of negotiations.

The leadership issues pose the question, “What are the roles and characteristics of effective SoS leadership?” This is addressed by incorporating views from multiple stakeholders while assessing the architecture’s quality. In addition, we maintain that the characteristics are similar to what an Acknowledged SoS manager would have while distributing funds and resources among systems for a joint operation. The SoS manager also has the opportunity to form his decision based on most likely future scenarios, thus imparting him an edge as compared to other models. This will improve the process of acquisition in terms of overall effectiveness, less cycle time and integrating legacy systems. Overall, the role of the leadership is presented a guide than someone who would foist his authority.

The third pain point question, “What are effective approaches to integrating constituent systems into a SoS? is addressed below. A balance has to be maintained during acquisition between amount of resources used and the degree of control exercised by the SoS manager on the constituent systems. The meta-architecture generation is posed as a multi-objective optimization problem to address this pain point. The constituent systems and the interfaces between them are selected while optimizing the resources such as operations cost, interfacing cost, performance levels etc. The optimization approach also evaluates the solutions based on views of multiple stakeholders integrated together using a fuzzy inference engine.

How can SE address capabilities and requirements? is the fourth pain point and is answered in this paragraph. Organizations that acquire large-scale systems have transformed their attitude to acquisition. Hence, these organizations now want solutions to provide a set of capabilities, not a single specific system to meet an exact set of specifications. During the selection process of systems it is ensured that, a single capability is provided by more than one system. The idea is to choose at least one systems having unique capability to form the overall capability of the SoS.

The fifth pain point on autonomies, emergence and interdependencies is one of the most important objectives of this research. This objective can be described as “How can SE provide methods and tools for addressing the complexities of SoS interdependencies and emergent behaviors?”. Each system has an autonomous behavior maintained through pre-assigned negotiation behaviors, differ operations cost, interfacing cost and performance levels while providing the same required capability. The interfacing among systems is encouraged to have net-centric architecture. The systems communicate to each other through several communication systems. This ensures proper communication channels. Together the behavior and net-centricity make it complex systems thus bringing out the emergence needed to address the mission.

FILA-SoS is an excellent integrated model for addressing the complexities of SoS interdependencies and emergent behaviors as explained in the above paragraphs.

As for the sixth pain point on testing, validation and learning goes, FILA-SoS has been tested on three notional examples so far the ISR, Search and Rescue (SAR) and the Toy problem for Aircraft Carrier Performance Assessment. For ISR (refer to Figure 2) a guiding physical example is taken from history. During the 1991 Gulf War, Iraqi forces used mobile SCUD missile launchers called Transporter Erector Launchers (TELS) to strike at Israel and Coalition forces with ballistic missiles. Existing intelligence, surveillance, and reconnaissance (ISR) assets were inadequate to find the TELs during their vulnerable setup and knock down time. The “uninhabited and flat” terrain of the western desert was in fact neither of those things, with numerous Bedouin goat herders and their families, significant traffic, and thousands of wadis with culverts and bridges to conceal the TELs and obscure their movement.

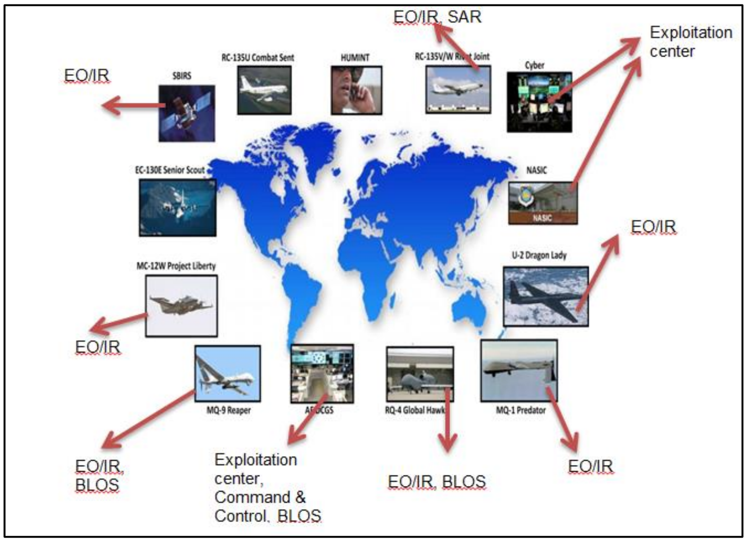


Figure 2 ISR System-of-Systems for Testing FILA-SoS

A Coast Guard Search and Rescue (SAR) (Figure 3) SoS engineering and development problem is selected for serving the Alaskan coast. Detailed information about this case study can be found in Dagli et al (2013). There is increasing use of the Bering Sea and the Arctic by commercial fisheries, oil exploration and science, which increases the likelihood of occurrence of possible SAR scenarios.

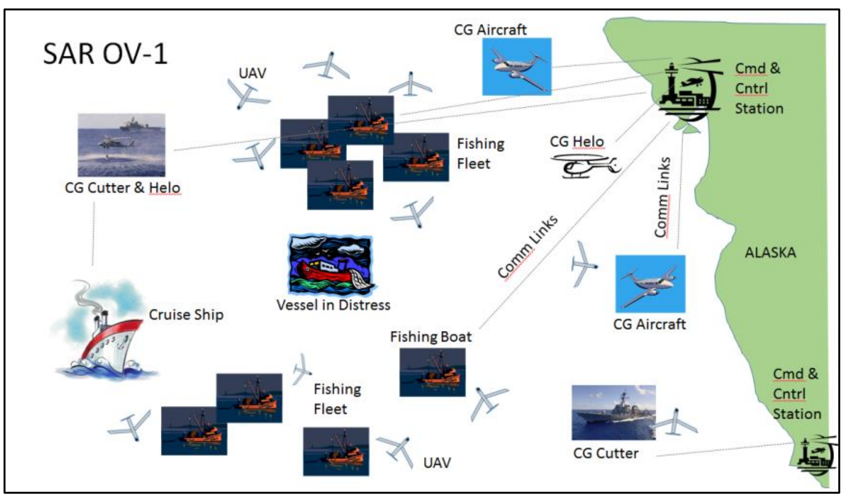


Figure 3 SAR System-of-Systems for Testing FILA-SoS

The toy problem for assessing the performance of the aircraft carrier involves multiple systems such as satellites, uav’s and ground station that support the aircraft carrier to fulfill the mission (refer to Figure 4). The results have been obtained for multiple waves of the evolution process for all the examples.

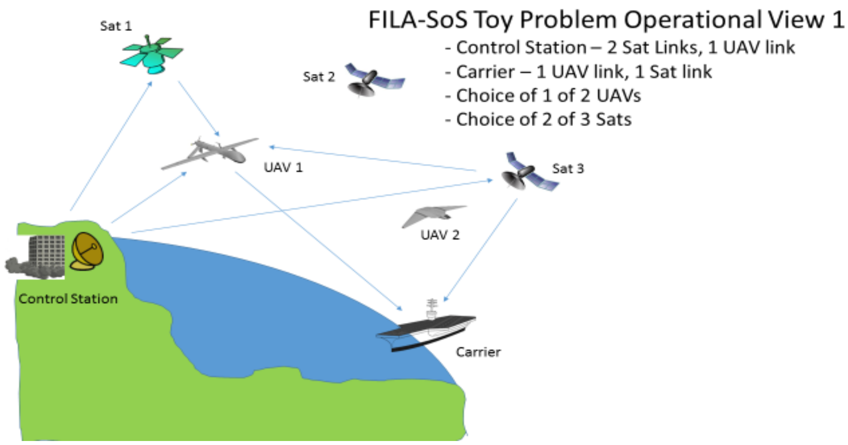


Figure 4 Aircraft Carrier Performance Assessment for Testing FILA-SoS

These example discussed above clearly show the domain independence of FILA-SoS.

FILA-SoS is a novel method of making sequential decisions over a period for SoS development. The goal is to apply the integrated model to dynamically evolve SoS architecture and optimize SoS architecture, design and validate through simulation tools. The integrated model structure can be applied to various application areas including development of dynamic water treatment SoS architecture, development of dynamic Air Traffic Management SoS, and development of autonomous ground transport SoS. FILA-SoS has a number of abilities that make it unique such as:

- Aiding the SoS manager in future decision making
- To assist in understanding the emergent behavior of systems in the acquisition environment and impact on SoS architecture quality
- To facilitate the learning of dynamic behavior of different type of systems (cooperative, semi-cooperative , non-cooperative)
- Identifying intra and interdependencies among SoS elements and the acquisition environment
- Modeling and application to a wide variety of complex systems models such as logistics, cyber-physical systems and similar systems
- Acting as a Test-bed for decision makers to evaluate operational guidelines and principles for managing various acquisition environment scenarios
- Appropriate to model SoS that evolve over a period of time under uncertainties by multiple wave simulation capability.

OVERVIEW OF THE FILA-SOS INTEGRATED MODEL

In this section an overview of FILA-SoS is described. The model developed called the FILA-SoS is using straightforward system definitions methodology and an efficient analysis framework that supports the exploration and understanding of the key trade-offs and requirements by a wide range system-of-system stakeholders and decision makers in a short time. FILA-SoS and the Wave Process address four of the most challenging aspects of system-of-system architecting:

- Dealing with the uncertainty and variability of the capabilities and availability of potential component systems.
- Providing for the evolution of the system-of-system needs, resources and environment over time.
- Accounting for the differing approaches and motivations of the autonomous component system managers.
- Optimizing system-of-systems characteristics in an uncertain and dynamic environment with fixed budget and resources

DEFINITION OF VARIABLES FOR SOS

This list comprises of the notation for variables used to solve the Acknowledged SoS architectural evolution problem:

C: Overall capability (the overall goal to be achieved by combining sub-capabilities)

c_j: $j \in \boldsymbol{J}$, $\boldsymbol{J}= \{1, 2, \ldots, M\}$:
Constituent system capabilities required

s_i: $i \in \boldsymbol{I}$, $\boldsymbol{I}= \{1, 2, \ldots, N\}$:
Total number of systems present in the SoS problem

Let $\boldsymbol{A}$ be a N x $M - matrix\ of\ a_{ij}\ where$

$a_{ij} = 1\ if$ capability j is possessed by system i

$a_{ij} = 0\ otherwise$

P_i: Performance of system i for delivering all capabilities $\sum_j a_{ij}$

F_i: Funding of system i for delivering all capabilities $\sum_j a_{ij}$

D_i: Deadline to participate in this round of mission development for system i

IF_{ik} Interface between systems $i\ and\ k$ s.t. $s \neq k$, $k \in I$

IC_i: The cost for development of interface for system i

OC_i: The cost of operations for system i

KP_r : $r \in \boldsymbol{R}$, $R= \{1, 2, \ldots, Z\}$:
The key performance attributes of the SoS

FA: Funding allocated to SoS Manager

$p= \{1, 2, \ldots, P\}$:
Number of negotiation attributes for bilateral negotiation

t_{max}: Total round of negotiations possible

t : Current round of negotiation (epochs)
t_{max}: Total round of negotiations possible
$V_{pi}^{SoS}(t)$: The value of the attribute p for SoS manager at time t for system i
$V_{pi}^{S}(t)$: The value of the attribute p for system i owner at time t
TQ: Threshold architecture quality

The model involves a list of stakeholders such as the Acknowledged SoS manager, system owners/managers, SoS environment etc.

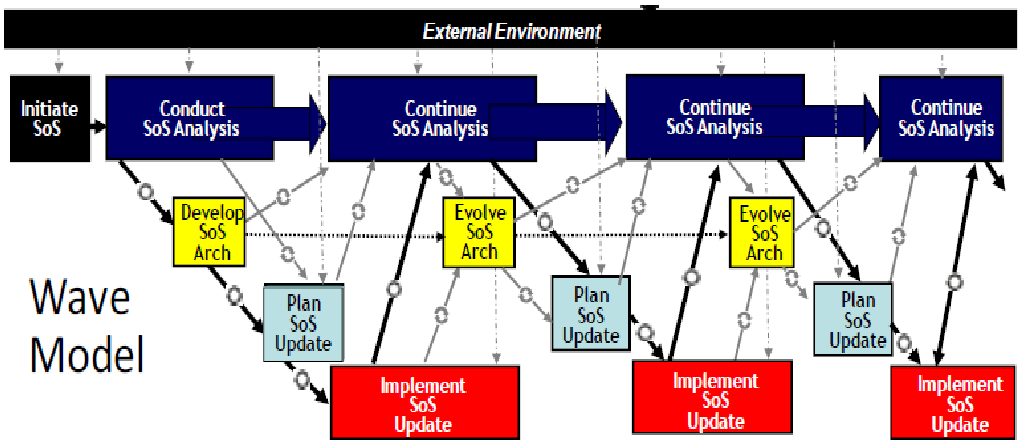


Figure 5 The Wave Model of SoS initiation, Engineering, and Evolution

FILA-SoS follows the Dahmann's proposed SoS Wave Model process for architecture development of the DoD acquisition process as depicted in Figure 5. FILA-SoS addresses the most important challenges of SoS architecting in regards to dealing with the uncertainty and variability of the capabilities and availability of potential component systems. The methodology also provides for the evolution of the system-of-system needs, resources and environment over time while accounting for the differing approaches and motivations of the autonomous component system managers. FILA-SoS assumes to have an uncertain and dynamic environment with fixed budget and resources for architecting SoS. The overall idea being to select a set of systems and interfaces based on the needs of the architecture in a full cycle called the wave. Within the wave, there may be many negotiation rounds, which are referred to as epochs. After each wave, the systems selected during negotiation in the previous wave remain as part of the meta-architecture whilst new systems are given a chance to replace those left out as a result.

Processes involved in the wave model and their analog in FILA-SoS can be explained through the first stage of Initializing the SoS. In terms of initializing, wave process requires to understand the SoS objectives and operational concept (CONOPS), gather information on core systems to support desired capabilities. This starts with the overarching capability C desired by Acknowledged SoS manager and defining the c_j or sub-capabilities required to produce capability C and FA, funding allocated to SoS Manager. These also form the input to the FILA-SoS for the participating systems s_i. FILA-SoS requires t_{max} the number of negotiation cycles, selection of the meta-architecture modelling procedure and system negotiation models assigned to participating systems.

The second stage is called the Conduct_SoS_Analysis. For the Wave process, it represents starting an initial SoS baseline architecture for SoS engineering based on SoS requirements space, performance measures, and relevant planning elements. For FILA-SoS the baseline architecture is called as the meta-architecture. Meta-architecture is basically picking up the systems s_i and their respective capabilities a_{ij}. Meta-architecture modelling requires the values for KP_t , the key performance attributes of the SoS, P_i (Performance of system i) , F_i (Funding of system i), and D_i deadline to participate in this round of mission development for system i which is assumed to be the total for all capabilities possessed by system i. The cost for development of a single interface for system i, IC_i and OC_i the cost of operations for system i is also needed at this stage of the model. The next step is the Develop/ Evolve SoS. In this case in terms of the Wave process essential changes in contributing systems in terms of interfaces and functionality in order to implement the SoS architecture are identified. Within FILA-SoS this signals the command to send connectivity request to individual systems and starting the negotiation between SoS and individual systems. This stage requires the number of negotiation attributes P for a bilateral negotiation between Acknowledged SoS manager and each systems i selected in the meta-architecture and t_{max} which denotes the total round of negotiations possible.

The next phase is Plan SoS Update in Wave process. In this, phase the architect plans for the next SoS upgrade cycle based on the changes in external environment, SoS priorities, options and backlogs. There is an external stimulus from the environment, which affects the SoS architecture. To reflect that in FILA-SoS determines which systems to include based on the negotiation outcomes and form a new SoS architecture. Finally, the last stage in Wave process is Implement SoS Architecture which establishes a new SoS baseline based on SoS level testing and system level implementation. In the FILA-SoS the negotiated architecture quality is evaluated based on KP_r, key performance attributes of the SoS. If the architecture quality is not up to a predefined quality or TQ the threshold architecture quality the Acknowledged SoS manager and systems i selected in the meta-architecture go for renegotiations. Finally the process moves on to the next acquisition wave. The evolution of SoS should take into account availability of legacy systems and the new systems willing to join, adapting to changes in mission and requirement, and sustainability of the overall operation. FILA-SoS also has the proficiency to convert the meta-architecture into an executable architecture using the Object Process Model (OPM) and Colored Petri Nets (CPN) for overall functionality and capability of the meta-architecture. These executable architectures are useful in providing the much-needed information to the SoS coordinator for assessing the architecture quality and help him in negotiating better.

Some of the highlights of FILA-SoS are described in terms of its capabilities, value added to systems engineering, ability to perform “What-if Analysis”, modularity of integrated models, its potential applications in the real world and future additions to the current version. The most important capability of FILA-SoS is it being an integrated model for modeling and simulating SoS systems with evolution for multiple waves. Secondly, all models within FILA-SoS can be run independently and in conjunction with each other. Thirdly, there are two model types that represent SoS behavior and various individual system behaviors. Finally, it has the capacity to study negotiation dynamics between SoS and individual systems.

The value added by FILA-SoS to systems engineering is it aids the SoS manager in future decision making, can help in understanding the emergent behavior of systems in the acquisition environment and its impact on SoS architecture quality. Besides, it has three independent systems behavior models, which are referred to as cooperative, semi-cooperative and non-cooperative. These behavior models are used to Study the dynamic behavior of different type of systems while they are negotiating with SoS manager. In addition, FILA-SoS assists in identifying intra and interdependencies among SoS elements and the acquisition environment.

FILA-SoS also can facilitate a "What-if" Analysis using variables such as SoS funding and capability priority that can be changed as the acquisition progresses though wave cycles. The parameter setting for all negotiation models can be changed and rules of engagement can be simulated for different combinations of systems behaviors.

Potential Application of FILA-SoS include complex systems models such as logistics, cyber-physical systems. In addition, it can act as test-bed for decision makers to evaluate operational guidelines and principles for managing various acquisition environment scenarios. While the future capabilities that we would like to be included are extending the model to include multiple interface alternatives among systems and incorporation of risk models into environmental scenarios.

INDEPENDENT MODULES OF FILA-SOS

The FILA-SoS has a number of independent modules that are integrated together for meta-architecture generation, architecture assessment, meta-architecture executable model, and meta-architecture implementation through negotiation. An overall view is presented in Figure 6.

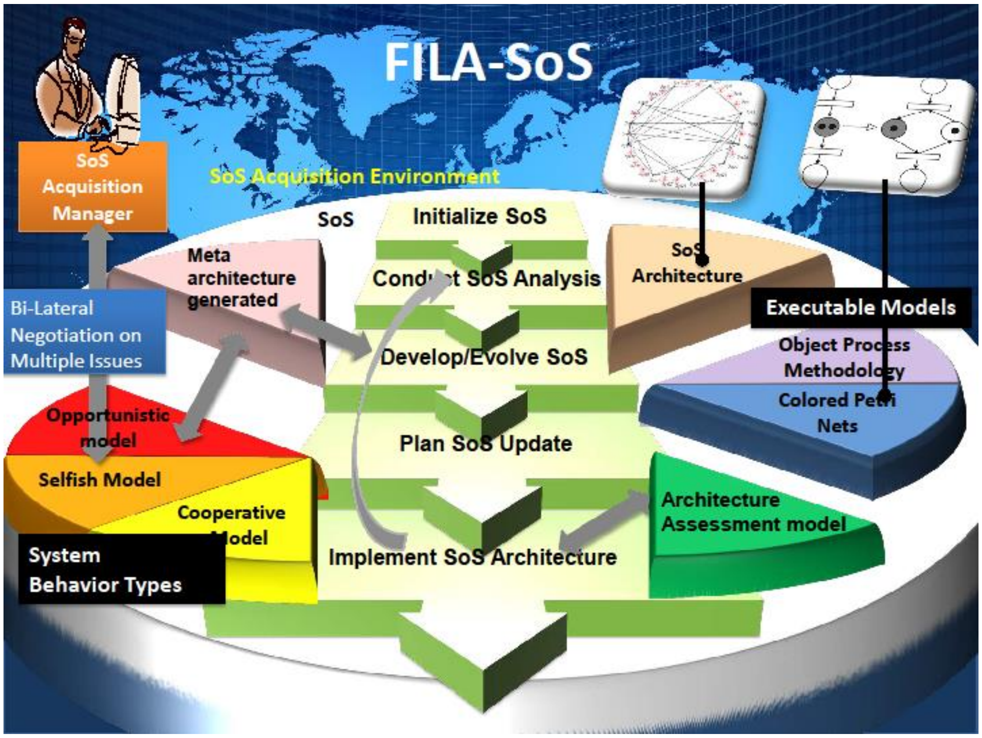


Figure 6 Integrated modules within FILA- SoS

All the independent models are listed below for reference:

- Meta-Architecture Generation Model
- Architecture Assessment Model
- SoS Negotiation Model
- System Negotiation Model: Non-Cooperative
- System Negotiation Model: Cooperative
- System Negotiation Model: Semi-Cooperative
- Executable Architecting Model: OPM & CPN
- Overall Negotiation Framework

The first meta-architecture generation method is fuzzy-genetic optimization model (Pape, Agarwal, Giammarco & Dagli, 2014). This model is based on evolutionary multi-objective optimization for SoS architecting with many key performance attributes (KPA). It also has a type-1 fuzzy assessor for dynamic assessment of domain inputs and that forms the fitness function for the genetic algorithm. It returns the best architecture (meta-architecture) consisting of systems and their interfaces. It is a generalized method with application to multiple domains such as Gulf War Intelligence/Surveillance/Reconnaissance Case and Alaskan Maritime Search and Rescue Case.

The second meta-architecture generation model is based on multi-level optimization (Konur & Dagli, 2014). In this model, architecting is done in two rounds: the first being the initiating the SoS by selecting the systems to be included in the SoS and then improving the SoS's performance by allocating funds to participating systems. The model is generic based on multiple attributes such as maximum performance, minimum cost and minimum deadline. It based on a Stackelberg game theoretical approach between the SoS architect and the individual systems.

The particle swarm optimization (Agarwal, Pape, & Dagli, 2014) technique for meta-architecture generation is similar to fuzzy-genetic model. Except for the fact that evolutionary optimization technique in this case is based on swarm intelligence. In addition, there are some new key performance attributes used to calculate the architectures quality. Cuckoo search optimization (Agarwal, Wang, & Dagli, 2014) based meta-architecture is again anew biologically inspired method of optimization. It has been shown that it in certain cases it performs better than PSO.

The first architecture assessment method is based on type-1 fuzzy logic systems (FLS) (Pape et al., 2013). The Key Performance Parameters (KPP) chosen are performance, affordability, flexibility, and robustness. It can capture the viewpoints of multiple stakeholders'. It can also accommodate any number of KPPs.

Another architecture assessment method is based on type-2 fuzzy modular nets (Agarwal, Pape & Dagli, 2014). The attributes used for evaluation were Performance, Affordability, Developmental Modularity, Net-Centricity and Operational Robustness. Type-1 fuzzy sets are able to model the ambiguity in the input and output variables. However, type-1 fuzzy sets are insufficient in characterizing the uncertainty present in the data. Type-2 fuzzy sets proposed by Zadeh (1975) can model uncertainty and minimize its effects in FLS (Mendel & John, 2002).

It is not possible to implement such meta-architecture without persuading the systems to participate, hence to address the issue a negotiation model is proposed based on game theory (Ergin, 2104). It is an incentive based negotiation model to increase participation of individual systems into Search and Rescue SoS. The model provides a strategy for SoS management to determine the appropriate amount of incentives necessary to persuade individual systems while achieving its own goal. The incentive contract is designed based on the objectives of the SoS and the individual systems. Individual system's objective is to secure highest incentives with minimal effort while the SoS manager's goal is to convince individual systems to join the SoS development while maximizing its own utility. Determining the incentives for individual systems can be formulated as a multi-constraint problem where SoS manager selects a reward for the individual system such that the reward will maximize SoS manager's expected utility while satisfying the constraints of the individual systems.

Another negotiation model based on clustering and neural networks is developed (Agarwal, Saferpour & Dagli, 2014). This model involves adapting the negotiation policy based on individual systems behavior that is not known to the SoS manager. The behavior is predicted by clustering the difference of multi-issue offers. Later the clustered data is trained using supervised learning techniques for future prediction.

Individual systems providing required capabilities can use three kinds of negotiation models based on their negotiation strategies non-cooperative Linear Optimization model, cooperative fuzzy negotiation model, and Semi-cooperative Markov chain model (Dagli et al., 2013).

Executable architectures are generated using a hybrid of Object Process Methodology (OPM) and Colored Petri Nets (CPN) (Agarwal, Wang, & Dagli, 2014), (Wang, Agarwal, & Dagli, 2014), and (Wang & Dagli, 2011). To facilitate analysis of interactions between the participating systems in achieving the overall SoS capabilities, an executable architecture model is imperative. In this research, a modeling approach that combines the capabilities of OPM and CPN is proposed. Specifically, OPM is used to specify the formal system model as it can capture both the structure and behavior aspects of a system in a single model. CPN supplements OPM by providing simulation and behavior analysis capabilities. Consequently, a mapping between OPM and CPN is needed. OPM modeling supports both object-oriented and process-oriented paradigm. CPN supports state-transition-based execution semantics with discrete-event system simulation capability, which can be used to conduct extensive behavior analyses and to derive many performance metrics.

INTEGRATED MODEL STRUCTURE

META-ARCHITECTURE GENERATION MODELS

MULTI-LEVEL OPTIMIZATION MODEL

This is a generic mathematical model for SoS architecting with multiple attributes such as minimizing cost, maximizing performance, and minimizing deadline. It follows an evolutionary optimization based approach for finding solutions to the problem. System selection with system contracting corresponds to a Stackelberg game between the SoS architect and the individual systems. The Stackelberg game is posed as a multi-objective multi-level optimization problem. The SoS architect is the leader and decides on which systems should be in the SoS architecture and the funds allocated to the individual systems. The systems are the followers and each individual system updates the performance level of the capabilities it can provide using the funds allocated by the SoS architect. For more details refer to Volume 2 which describes Meta-Architecture Generation Multi-Level Model.

What-if Analysis that can be done using the model to answer questions such as *What happens if selected attributes such as performance, cost, and deadline of the systems change?, What happens if some of the systems are not available or they cannot provide some of the capabilities they could provide? and What happens if systems can provide additional capabilities?*

The value of the model can be adjudged by its ability to consider different objectives for SoS architecting, incorporating practical settings of SoS architecting and the ability of determining the right ways of fund allocation to individual systems for improvement.

The potential applications include Initiating the negotiation process by returning a set of SoS. This model can be applied in any SoS domain such as logistics, network-centric systems, cyber-physical systems and supply chain management.

The possible future capabilities embrace modeling negotiation within SoS architecting, modeling competition among the systems, modeling flexibility of the systems and how to incentivize systems to become flexible. This model can be modified for a specific potential application of a SoS concept.

FUZZY GENETIC OPTIMIZATION MODEL

Fuzzy-genetic optimization model is another alternative for meta-architecture generation. The model capabilities include evolutionary multi-objective optimization model for SoS architecting with many key performance attributes (KPA). It involves dynamic assessment of domain inputs and returns the best architecture consisting of systems and their interfaces. For more details refer to Volume 3 which illustrates the second meta-architecture generation model known as the Fuzzy-genetic optimization model.

What-if Analysis that can be done using the model to answer questions such as *What happens if selected attributes such as performance, cost, and deadline of the systems change?, How will the range of different KPA's over the set of architectures vary the architectures quality?, What happens if number of systems having net centric capability reduces?* .

This model adds to the existing meta-architecture generation techniques, it takes into account the net-centricity of the architecture and provides a fuzzy assessor for several competing objectives.

The potential application of this model comprise of finding architectures for multiple waves, domain independence and therefore can be applied to logistics, network-centric systems, cyber-physical systems and supply chain management.

Possible future capabilities consist of adding multiple interfaces among a set of systems e.g. energy flow, information, and mechanical, estimating of component and interface complexity for better measurement of architecture quality, and modifications in the model for a specific potential application.

ARCHITECTURE ASSESSMENT MODEL

This model is used to calculate the quality for the SoS architecture based on the KPAs selected by the stakeholders or the SoS manager. The capabilities of this model can be summed up as the ability to capture non-linearity in key performance attribute tradeoffs, accommodate any number of attributes for a selected SoS capability, capture multiple stakeholder's understanding of key performance attributes. It also provides for algorithms to determine the value of various attributes generally used in SoS. Finally, it gives a numerical value based on fuzzy sets and fuzzy inference engine to evaluate the quality of a given architecture based on the value of the attributes. Volume 4 describes an Architecture Assessment Model.

The Model Value lies in exploring the architecture 'space' with the "What-if" analysis, the stakeholders can develop a better understanding of how component systems can fit and work together and providing a more realistic assessment than utility functions.

What-if Analysis that can be done using the model to answer questions such as *what is the effect of change in Attribute definitions and algorithms based on domain?, Can the model be adjusted for different domains and stakeholder's?, What happens if number of attributes can be added and old ones discarded? and What is the effect of modifying relative priorities of the attributes by prioritizing assessment rules?*

The potential application of this model comprise of finding new ways for systems to work together, discovering more cost effective SoS arrangements and aiding in negotiations with component systems to build an SoS.

Possible future capabilities entail improved visualization of the impact of many variables in SoS architecture and design, and automated adjustment of model parameters.

COOPERATIVE SYSTEMS NEGOTIATION MODEL

The capabilities of this systems negotiation model are that it is computationally scalable to a large number of issues and system types. It presents a semi-cooperative behavior and can negotiate multiple issues simultaneously. It also illustrates the cognitive and financial aspects of human negotiations. Overall, it is a bilateral negotiation mechanism. Volume 5 specifically describes the Cooperative System Negotiation Model.

The model provides solutions in complex automated negotiation scenarios and the model predictions can be used for similar situations that were not previously modeled. It can identify counterintuitive results or causal relationships. It has the ability to work with other negotiation models and can work as an independent module.

The what-if analysis includes changing the preferences and the strategy considerations of the systems, which are private, i.e., they are not known to the other systems or manager. Simulations with changing parameter values for various scenarios can yield valuable insight. It is useful for knowledge discovery and agent learning tools.

The potential application of this model comprise of logistics, supply chain, cyber-physical systems, e-commerce, decision-making support etc.

Possible future capabilities entail problem solving using a multi-criteria group decision-making approach to handle multiple offers from the SoS manager.

NON-COOPERATIVE SYSTEM NEGOTIATION MODEL

The non-cooperative negotiation protocol has the ability to define how negotiations are initiated, continued, and terminated. It presents a decision framework of contract negotiation for individual systems. It characterizes the individual system's participation capability and negotiation behavior. It is able to generate negotiation alternatives in the presence of multiple conflicts. It consists of three optimization models that help search alternatives with a minimum impact of conflicts. Besides, it contains conflicts evaluation model that estimates negotiation outcomes for each alternative. Volume 6 goes on to describe the Non-Cooperative System Negotiation Model in detail.

The value of the model can be expressed as a negotiation model for individual systems in the setting of SoS acquisition, which can be used by the SoS manager to assess and train the SoS acquisition abilities/strategies. It is a realistic model that poses challenging responses to the SoS manager's request for participation, which the SoS manager can use for developing an understanding of individual systems that have self-interests and are strategic negotiators, and also developing strategies for handling them.

What-if Analysis that can be done using the model, to answer questions such as *What if an individual system is more/less capable than the SoS expects?, What if an individual system is more/less cooperative than the SoS expects?, What if an individual system is a strategic* *negotiator? and Whether an individual system can be impacted by negotiation strategies of the SoS, such as monetary incentive, time pressure, and others; and how? .*

Individual suppliers/service providers in the negotiation of supply-procurement contracts can use the negotiation model. Individual persons in the development of dynamically reconfigurable teams can also use it.

Possible future capabilities entail problem solving using an intelligent algorithm that can determine an optimal alternative in a fast manner. A learning mechanism with which the individual systems model can effectively calibrate the guess of SoS's utility functions can also be added. A broader band of negotiation strategies is necessary to handle a wider range of negotiation scenarios.

SEMI-COOPERATIVE SYSTEM NEGOTIATION MODEL

Model has the capability of being flexible or opportunistic: i.e., cooperative or non-cooperative. It is a Markov-chain based model designed for handling uncertainty in negotiation modeling in an SoS. Volume 7, illustrates the Semi-Cooperative System Negotiation Model.

The value can be measured as being useful for testing opportunistic behavior prevalent in industry partners exhibiting risk-prone behavior. It has the ability to model very selfish to very selfless behavior on a continuum using a numerical user-adjustable scale.

The what-if analysis includes testing scenarios for given performance criteria and given number of interacting systems in an SoS and the ability to determine budget and schedule for any given negotiation model for an SoS.

Potential applications include modeling behavior of defense firms competing to obtain contract. It can also model project durations for any system within the SoS.

Possible future capabilities include testing for risk-prone behavior of systems within an SoS and implementation of machine learning models for SoS controller.

INCENTIVE BASED NEGOTIATION MODEL

The Model Capabilities include a Game theoretic negotiation model that will maximize the welfare for parties involved in the negotiation. The SoS negotiation model is based on utility function that take into account local objectives for the individual systems as well as global SoS objective. The models possess an incentive contract design to persuade uncooperative systems to join the SoS development. Volume 8 explains the SoS negotiation model for System of Systems.

The value inherent in the model can do a analysis of how incentives can be used to improve lack of collaboration in SoS acquisition which is a leading problem in SoS acquisition effectiveness. An analysis of how incentives can be used to ensure effective SoS mission performance can also be done.

The What-if Analysis includes an examination of incentive mechanisms under different behavioral settings including such as when does selfish behavior dominates the acquisition environment or when does opportunistic behavior dominate or when does cooperative behavior dominate. Various incentive mechanisms can be analyzed when there is uncertainty in individual system performance outcomes.

Possible applications include it as a tool for evaluating operational guidelines and principles for incentive contract design for SoS acquisition under various acquisition environment scenarios.

Future additions could include the study of risk taking preferences of individual systems and SoS manager and its impact on incentive contract design. Another possibility is to have an incentive contract design for individual system groups that interact with each other.

MODEL FOR BUILDING EXECUTABLE ARCHITECTURE

The capabilities can be described as ability to capture the interactions between components of a system or subsystems in SoS. It can capture the dynamic aspect of the SoS and simulate the behavior of the SoS. It can access various behavior related performance of the SoS and access different constitutions or configurations of the SoS. Volume 9 illustrates the process of building Executable Architectures for SoS.

The value of the model lies in examining whether and how well the constituent systems can collaborate with each other in delivering the desired capabilities when the SoS is in operation. It can also provide a detailed, quantitative performance analysis.

What-if Analysis has the power that can be used in assessing the impact of changes in system parameters, constitution, and configuration to the overall functionality and capability of the SoS. It can assess the system performance under various operational scenarios. This model forms a good support of hierarchical modeling and can be used independently.

Possible applications include where interactions between constituent systems or system components are critical to fulfillment of the overall functionality and capability of the SoS. It can also be used in situations where there is need to access the emergent behavior of the SoS.

Future additions to the model can be to automate the model construction, alternative generation and performance analysis process. Another possibility can be to examine all possible operational states of the SoS.

IMPLEMENTING FILA-SOS INTEGRATED MODEL ON NOTIONAL SYSTEM OF SYSTEMS

TOY PROBLEM FOR AIRCRAFT CARRIER PERFORMANCE ASSESSMENT

There are majorly five kinds of capabilities in this notional example namely; control station, type-A satellite, UAV, type-B satellite and aircraft carrier. Figure7. represents a sample scenario for the notional SoS used for assessing the performance of the aircraft carrier involves multiple systems such as satellites, UAV’s and ground station that support the aircraft carrier to fulfill the mission.

System 1 is command control, systems 2-9 are Satellite type-A, systems 10-15 are UAV types, systems 16-21 are Satellite type-B and there is only one system 22 representing capability aircraft carrier. The key performance attributes selected are Criticality of Dependency (COD) (Garvey & Pinto, 2009), Strength of Dependency (SOD) (Guariniello & DeLaurentis, 2013) and performance of carrier.

It is modeled as a directed network SoS such that the network structure is preserved while opting for different alternatives for the same capability during meta-architecture selection methods. The nodes represent either the system alternatives or the capabilities present to be acquired.

The meta-architecture generation model used here is multi-level optimization and the assessment model is based on type-1 fuzzy sets. The assessment model is modified to incorporate the new key performance attributes defined for this problem. The system behavior models include cooperative, non-cooperative and semi-cooperative whereas the SoS negotiation model is based on incentivized game theory based contracting.

Sample Scenario for Aircraft Carrier Performance Problem

System	Type Sub-System	Cap ability Number	Value Added to SoS	Time to Develop, Epochs	System Number
Command	Ground Control	1	5-50	1	1
SAT	SAT-Type 1	2	20-50	1	2-9
UAV	UAV Types	3	2.5-10	0	10-15
SAT	SAT-Type 2	4	20-50	1	16-21
Carrier	Aircraft Carrier	5	45-50	1	22

Sys no	Behavior
1,3,5,9,10,13,14,22	Non-Cooperative
2,4,6,7,8,15,16,17	Cooperative
11,12,18,19,20,21	Semi-Cooperative

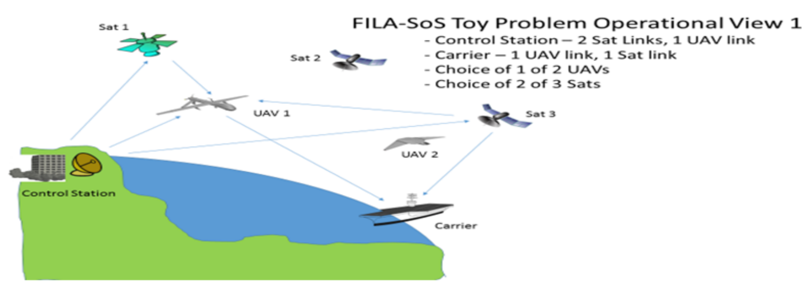
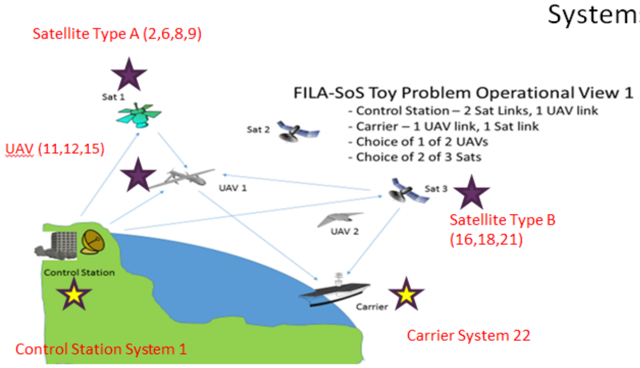


Figure 7 Sample Scenario for Notional SoS Problem Developed for FILA-SoS

Figure 8 shows the systems selected in the meta-architecture during wave 1 of SoS evolution. Figure 9 shows the final architecture that is agreeable between the SoS manager and the systems after negotiation during wave 1. The values of the key performance attributes for the best meta-architecture and the overall quality of the architecture are given in Figure 8. The SOD is 0.16, COD is 55, Performance of Carrier is 79 and the overall quality is 2.98 on a scale of 1 to 4. The same concept holds true for the negotiated architecture.

Meta-Architecture Wave 1



Systems selected in the Meta-Architecture

Systems Selected
Ground Control (1)
Satellite Type A (2,6,8,9)
UAV (11,12,15)
Satellite Type B (16,18,21)
Carrier (22)

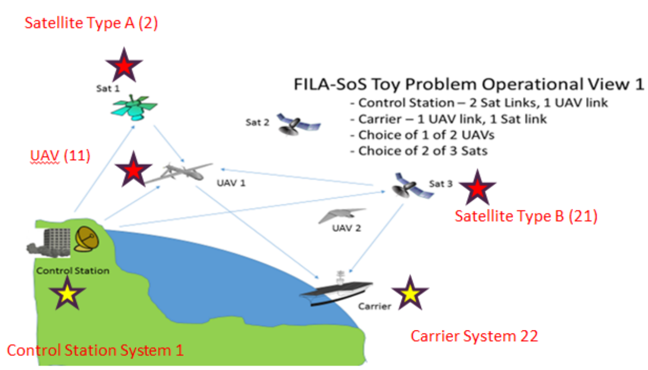
Assessment for the meta-architecture =2.98

Key Attribute values:

- Strength of Dependency (SOD)=0.16
- Criticality of Dependency (COD)=55
- Performance of Carrier=79

Figure 8 Integrated Modules within FILA-SoS

Negotiated Architecture Wave 1



Systems selected after negotiation S_i

Sys no	Behavior
1	Non-cooperative
2	cooperative
11	Semi-cooperative
21	Semi-cooperative
22	Non-cooperative

Assessment for the meta-architecture =2.1

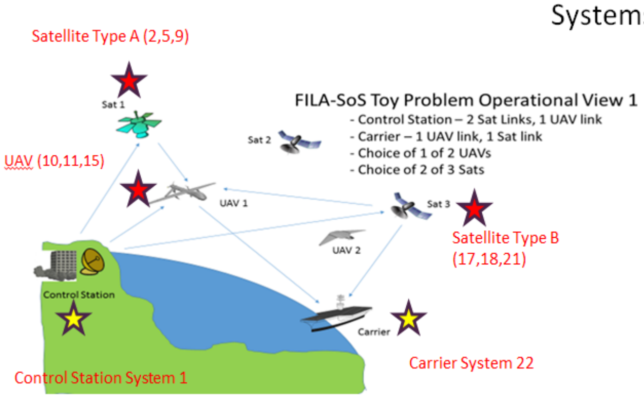
Key Attribute values:

- Strength of Dependency (SOD)=0.12
- Criticality of Dependency (COD)=55
- Performance of Carrier=60

Figure 9 Integrated Modules within FILA-SoS

Figures 10 shows the systems selected in the meta-architecture during wave 2 of SoS evolution. Figure 11 shows the final architecture that is agreeable between the SoS manager and the systems after negotiation during wave 2.

Meta-Architecture Wave 2



Systems selected in the Meta-Architecture

Systems Selected
Ground Control (1)
Satellite Type A (2,5,9)
UAV (10,11,15)
Satellite Type B (17,18,21)
Carrier (22)

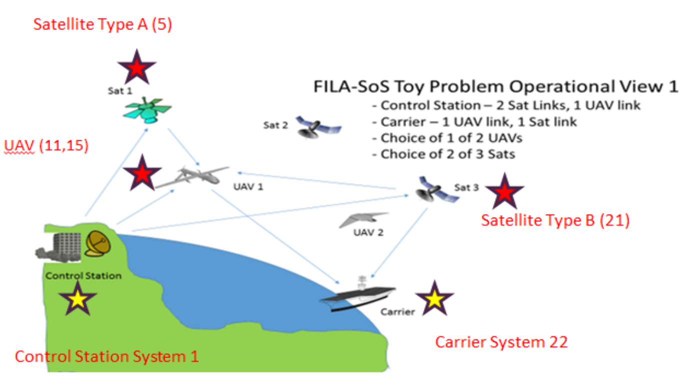
Assessment for the meta-architecture =2.5
Key Attribute values:

- Strength of Dependency (SOD)=0.4
- Criticality of Dependency (COD)=35
- Performance of Carrier=81

Figure 10 Integrated Modules within FILA-SoS

Negotiated Architecture Wave 2

Systems selected after negotiation S_i



Sys no	Behavior
1	Non-cooperative
5	cooperative
11,15	Semi-cooperative
21	Semi-cooperative
22	Non-cooperative

Assessment for the meta-architecture =1.2

Key Attribute values:

- Strength of Dependency (SOD)=0.03
- Criticality of Dependency (COD)=43
- Performance of Carrier=71

Figure 11 Integrated Modules within FILA-SoS

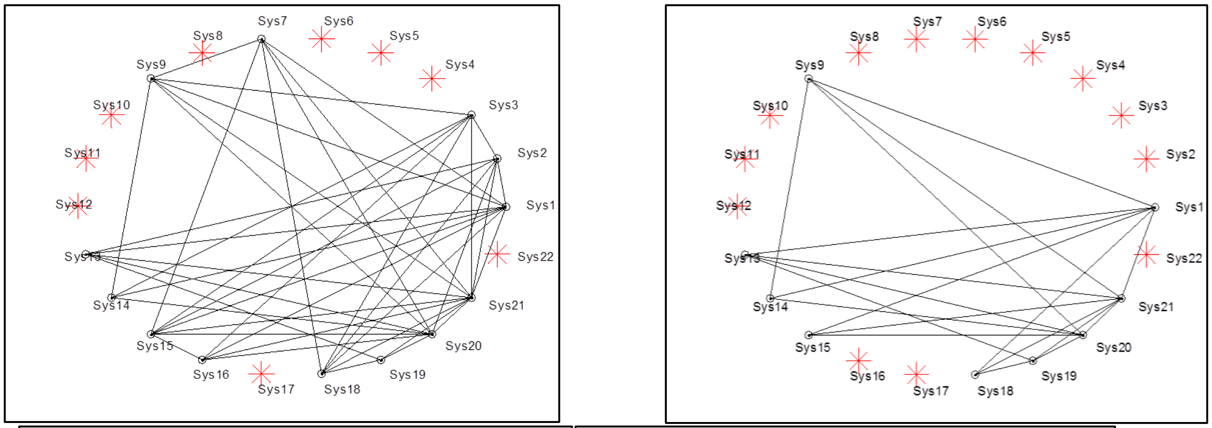
ILLUSTRATION OF THE FIRST WAVE IN ISR THROUGH FILA-SOS

This section describes the evolution of SoS as architectures are generated and implemented sequentially for 3 waves for ISR SoS. Table 2 describes the domain specific inputs, and graphs represent systems selected and their interconnections. There are 22 systems and 5 capabilities namely; electro-optic/infrared, infrared, exploitation, communication and ground control as shown in Table 2. The meta-architecture generation model used here is Fuzzy-Genetic optimization (Pape, Agarwal, Giammarco, & Dagli, 2014). The SoS manager disseminates the information to a network of systems. The information involves performance required, funding provided, and deadlines within which certain tasks have to execute. Each system in the networks interprets the information and makes a decision based on his behavior.

The left side of the Figure 12 is the meta-architecture whereas the right side is the negotiated architecture. The set of systems selected and the interfaces is presented as circular graph. The systems not selected are marked as red asterisks. Architecture assessment is done through fuzzy logic based rules (Pape, Giammarco, Colombi, Kilicay-Ergin, Rebovich, 2013). These rules capture non-linearity in key performance attribute tradeoffs. Moreover, fuzzy rules are able to understand multiple stakeholders' understanding of key performance attributes. Relative priorities of the attributes can also be accommodated by prioritizing assessment rules.The output is the quality of a given architecture based on the value of the attributes. The higher the values (on a scale of 4) better the architecture. The architecture quality of the negotiated architecture is always less than or equal to the meta-architecture. This is because the meta-architecture is the best possible architecture the SoS manager can achieve. In this case it is less than the meta-architecture quality.

Table 2 ISR domain specific inputs Wave 1

System	Type Capability	Cap ability Number	Coverage sq mi/hr;	Develop $M/ epoch/ interface	Operate $K/hr per system	Time to Develop, Epochs	System Number
Fighter	EO/IR	1	500	0.2	10	1	1
Trainer	EO/IR	1	2000	2	2	1	2-3
UAV	EO/IR	1	50000	0	15	0	4-8
DSP	IR	1	8000	0.1	1	1	9
Fighter	Radar	2	3000	0.7	10	1	10-12
JSTARS	Radar	2	10000	0.1	18	1	13
Theatre	Exploit	3	5000	2	10	1	14-15
CONUS	Exploit	3	25000	0.2	0	0	16
Control	Cmd &	4	10000	1	2	1	17-18
LOS Link	Comm	5	10000	0.2	0	1	19-20
BLOS Link	Comm	5	5000	0.5	3	1	21-22



Assessment for the meta-architecture =3.47
Key Attribute values:
Performance=2.16; Flexibility=4
Affordability=3.5 ; Robustness=3.91

Assessment for the final-architecture =2.5
Key Attribute values:
Performance=1.5; Affordability=3.72
Flexibility=2; Robustness=2

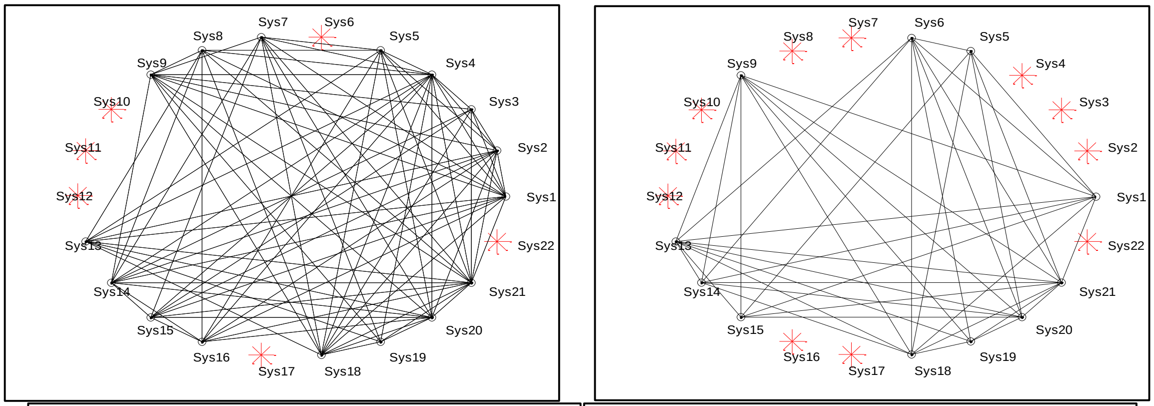
Figure 12 ISR SoS Wave 1 Meta-Architecture (left) and Negotiated Architecture (right)

ILLUSTRATION OF THE SECOND WAVE IN ISR THROUGH FILA-SOS

The systems highlighted in yellow were selected at the end of negotiation process in the previous wave in Table 3. Hence, they are preserved or maintained in the next wave meta-architecture. New systems replace the other systems with different value of key attributes. To make things simple we have not changed the order of the systems from one wave to the next although that is possible.

Table 3 ISR domain specific inputs Wave 2

System	Type Sub-System	Cap ability Number	Coverage sq mi/hr;	Develop $M/ epoch/	Operate n///hr$K/hr per system	Time to Develop, Epochs	System Number
Fighter	EO/IR	1	500	0.2	10	1	1
Trainer	EO/IR	1	12000	0.1	8	1	2-3
UAV	EO/IR	1	8000	0.5	2.5	1	4-8
DSP	IR	1	8000	0.1	1	1	9
Blimp	Radar	2	20000	0.5	12	1	10-12
JSTARS	Radar	2	10000	0.1	18	1	13
Theatre	Exploit	3	5000	2	10	1	14-15
MOBExp	Exploit	3	15000	0.1	0.2	0	16
MOBC2	Exploit	4	12000	1	2	0	17
Control	Cmd &	4	10000	1	2	1	18
LOS Link	Comm	5	10000	0.2	0	1	19-20
BLOS Link	Comm	5	5000	0.5	3	0	21
Mil-Sat	Comm	5	15000	1	5	1	22



Assessment for the meta-architecture =3.61
Key Attribute values
Performance=2.28; Affordability=3.09
Flexibility=4; Robustness=3.77

Assessment for the meta-architecture =3.1
Key Attribute values
Performance=1.94; Affordability=3.6
Flexibility=3; Robustness=3.16

Figure 13 ISR SoS Wave 2 Meta-Architecture (left) and Negotiated Architecture (right)

SEARCH AND RESCUE PROBLEM

ILLUSTRATION OF THE FIRST WAVE IN SAR THROUGH FILA-SOS

The search and rescue problem follows suit as the other problems discussed above. It has 22 systems and the distribution of the 5 capabilities can be read from Table 5. Table 4 lists the domain inputs required to form the meta-architecture. The meta-architecture generation model used here is Fuzzy-Genetic optimization (Pape, Agarwal, Giammarco, & Dagli, 2014).

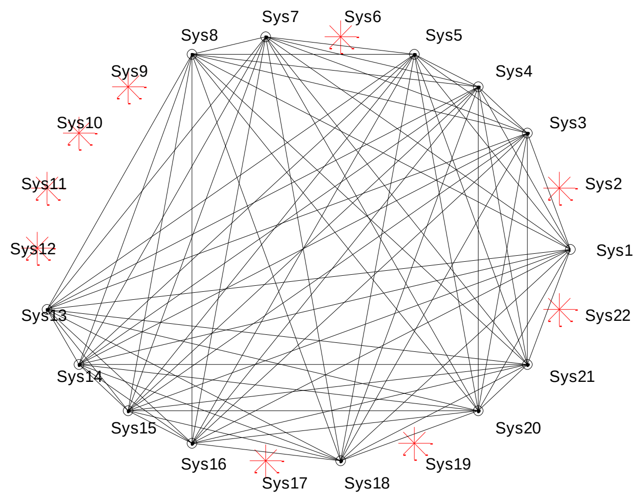
Table 4 SAR domain inputs for Wave 1

SysNo	Type	Capability	I/FDevCost	OpsCost/hr	Perf	DevTime
1	Cutter	3	0.03	2	12	1
2	Cutter	3	0.03	2	12	1
3	Helicopter	3	0.1	2	20	1
4	Helicopter	3	0.1	2	20	1
5	Aircraft	4	0.1	5	10	1
6	Aircraft	4	0.1	5	10	1
7	UAV	1	0.1	0.1	7	1
8	UAV	1	0.1	0.1	7	1
9	UAV	2	0.1	0.1	7	1
10	UAV	2	0.1	0.1	7	1
11	UAV	2	0.1	0.1	7	1
12	UAV	2	0.1	0.1	7	1
13	Fish Vessel	2	0.03	0.5	4	1
14	Fish Vessel	2	0.03	0.5	4	1
15	Fish Vessel	2	0.03	0.5	4	1
16	Fish Vessel	2	0.03	0.5	4	1
17	Civ Ship	3	0.05	2	8	1
18	Coord Ctr	5	0.05	0.5	5	1
19	Coord Ctr	5	0.05	0.5	5	1
20	Communications	5	0.02	0.03	1	0
21	Communications	5	0.02	0.03	1	0
22	Communications	5	0.02	0.03	1	0

Table 5 List of capabilities for SAR

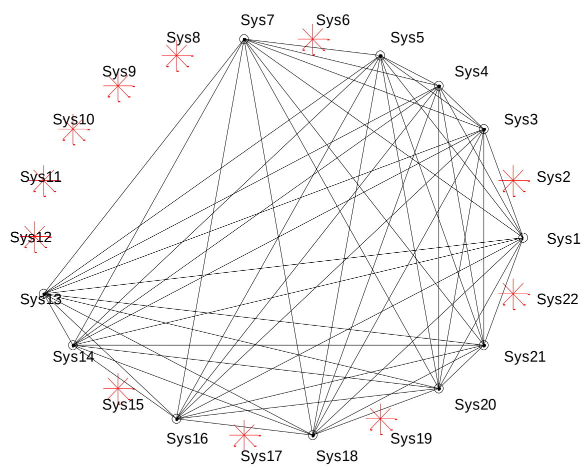
Capability	CapName
1	IR – range 3 nm
2	Night Vision – range 3 nm/ Visual – range 3 nm
3	Remove survivor(s) to Emergency Medical Care
4	Speed 300 mph
5	Communication

Figure 14 is the meta-architecture for SAR during wave 1. The architecture quality is high, based on scale of 4. As can be seen in Figure 15 the negotiated architecture quality slower compared to meta-architecture quality since the SoS manager was not able to have very successful negotiation to form a implementation.



Quality	**3.78**
Performance	3.36
Affordability	3.66
Flexibility	4
Robustness	3.68

Figure 14 SAR SoS Wave 1 Meta-Architecture (left) as Undirected graph and KPP Values (right)



Quality	**1.29**
Performance	1
Affordability	4
Flexibility	4
Robustness	1

Figure 15 SAR SoS Wave 1 Negotiated Architecture as Undirected Graph (left) and KPP Values (right)

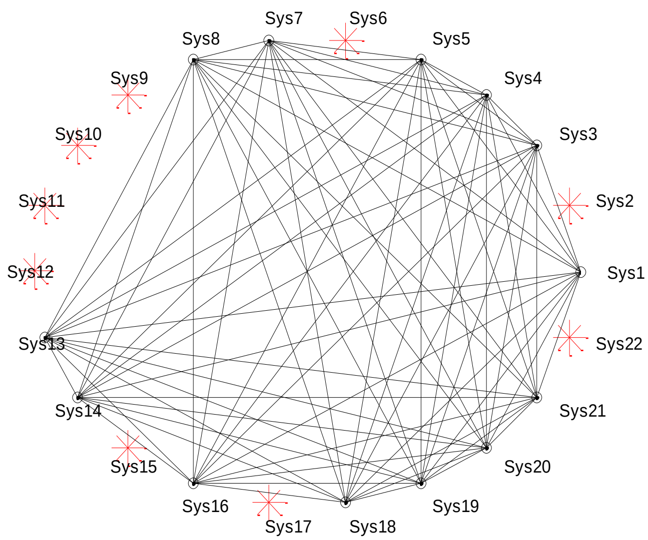
ILLUSTRATION OF THE SECOND WAVE IN SAR THROUGH FILA-SOS

The systems highlighted in yellow were selected at the end of negotiation process in the previous wave. Hence, they are preserved or maintained in the next wave meta-architecture. New systems replace the other systems with different value of key attributes. To make things simple we have not changed the order of the systems from one wave to the next although that is possible. 11 systems form the previous wave are retained to forma the meta-architecture in wave 2. The strategy deployed here is to negotiate bilaterally between the participating system and the SoS manager. Systems with different behaviors respond differently to each offer made by the SoS manager. The number of rounds of negotiation is predefined and in between, the SoS may accept or reject the offer made by the systems. Following which there is no more negotiation. The systems negotiation models used are the same as described previously through the SoS negotiation model illustrated earlier. It is quite predictable to have cooperative and semi-cooperative systems selected more often than non-cooperative systems. Final systems behavior configuration changes in the architecture based on number of waves.

Table 6 SAR domain inputs for Wave 2

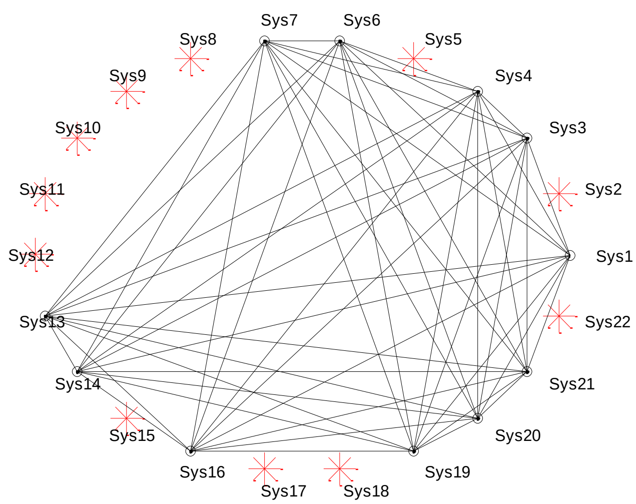
SysNo	Type	Capability	I/FDevCost	OpsCost/hr	Perf	DevTime
1	Cutter	3	0.03	2	12	1
2	Cutter	3	0.05	2.5	10	1
3	Helicopter	3	0.1	2	20	1
4	Helicopter	3	0.1	2	20	1
5	Aircraft	4	0.1	5	10	1
6	Aircraft	4	0.5	8	20	1
7	UAV	1	0.1	0.1	7	1
8	UAV	1	0.4	0.2	8	1
9	UAV	2	0.4	0.2	8	1
10	UAV	2	0.4	0.2	8	1
11	UAV	2	0.4	0.2	8	1
12	UAV	2	0.4	0.2	8	1
13	Fish Vessel	2	0.03	0.5	4	1
14	Fish Vessel	2	0.03	0.5	4	1
15	Fish Vessel	2	0.02	0.3	6	1
16	Fish Vessel	2	0.03	0.5	4	1
17	Civ Ship	3	0.05	4	15	1
18	Coord Ctr	5	0.05	0.5	5	1
19	Coord Ctr	5	0.03	0.1	5	1
20	Communications	5	0.02	0.03	1	0
21	Communications	5	0.02	0.03	1	0
22	Communications	5	0.01	0.05	1.5	0

The negotiated architecture quality is lower than the meta-architecture quality. Multi-level optimization model was used for meta-architecture generation and. Type -1 fuzzy assessor was used for architecture assessment. The negotiation modules are the same as described in previous wave.



Quality	**3.74**
Performance	3.49
Affordability	3.67
Flexibility	4
Robustness	3.65

Figure 16 SAR SoS Wave2 Meta-Architecture (left) as Undirected Graph and KPP Values (right)



Quality	**1.55**
Performance	2.45
Affordability	1
Flexibility	4
Robustness	2.06

Figure 17 SAR SoS Wave2 Negotiated Architecture (left) as Undirected Graph and KPP Values (right)

CONCLUDING REMARKS

The report offers detailed insights on the SoS architecture evolution through FILA-SoS methodology. It also successfully demonstrates the application of FILA-SoS integrated model on three notional examples and provides the solutions. Other volumes offer further details on each model within the FILA-SoS version 1.0.

Three research questions namely are answered in volumes 12-14:

- What is the impact of different constituent system perspectives regarding participating in the SoS on the overall mission effectiveness of the SoS?
- How do differing levels of cooperativeness in participating in the SoS impact the ability and timeliness of a group to agree on a SoS or system architecture? Or impact the ability to effectively use the architecture already in place?
- How should decision-makers incentivize systems to participate in SoS, and better understand the impact of these incentives during SoS development and effectiveness?

Volume 12 provides a model to answer the first research question, whereas Volumes 13, 14 provide two different approaches to answer the second research question, and Volume15 answers the third research question. New models are developed to be implemented for FILA-SoS version 2.0. They are presented in details in other volumes.

The FILA-SoS integrated model attempts to add value by improving the acquisition process of SoS as well as diversification through using multiple modular techniques. The present model can be adjusted for different domains and stakeholders as well as new attributes can be added and old ones discarded. The validation of FILA-SoS and other modules contained in it with a real life example is presented in Volume 17.

APPENDIX A: LIST OF PUBLICAS RESULTED AND PAPERS SUBMITTED FROM FILA-SOS RESEARCH

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