A SYSTEMS APPROACH TO ARCHITECT COHERENT SYSTEM OF SYSTEMS CAPABILITIES

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ABSTRACT

Architecting of coherent system-of-systems (SoS) capabilities is complex due factors such as the diverse range of stakeholders and evolving requirements. Left to themselves, these individual stakeholders at the system requirements definition and implementation stages may demand for optimization of individual systems of their interests. This would collectively result in local optimization at the system-level at the expense of SoS-level or even enterprise-level effectiveness. This paper proposes an approach to coherently architect SoS capabilities. This approach is premised on the assumption that a "top-down" leadership approach is applicable to establish the required reporting structures and relationships in the technical community. The approach attempts to weave in the considerations of limited shared resources and common technological solutions across the national defense enterprise into the process of architecting an SoS that would fulfil a large-scale mission capability.

BACKGROUND

The advent of information technology and network-centric concepts for military systems has led to considerable interest in the study of system-of-systems (SoS). An SoS is defined as an interoperating collection of component systems that produce results unachievable by the individual systems alone [INCOSE Systems Engineering Handbook v3]. Synergistic behavior or positive emergent behavior of an SoS is envisaged to provide its operational users an asymmetric advantage over adversaries employing a collection of similar but less integrated military systems. Over the past few years, there has been growing interest to examine SoS issues via systems architecting [Tan et al 2008].

However, it is not easy to attain this pinnacle state of an SoS. One challenge is the alignment of specific stakeholders of constituent systems that form the SoS. Specifically, the stakeholders we refer here are operational managers from the military community and system managers from the technical community, who conceive and implement individual system solutions. This can occur during the system requirements definition stage or during the implementation stage. Maier alluded to this when he defined one of the principal characteristics of an SoS to be the managerial independence of the SoS' constituent systems [Maier 1996]. These operational and system managers would likely focus on the optimization of individual systems of their interest. However, such local optimization at the system-level may result in sub-optimal effectiveness at the SoS-level or even enterprise-level.

It could be very challenging to attain a “global optimum” at the SoS-level or enterprise-level by relying primarily on self-synchronization of multiple operational and system managers. More likely, a deliberate “top-down” leadership approach is required to establish and enforce SoS-level or enterprise-level priorities. This does not mean that project management of the SoS' constituent systems should all be centrally conducted, because process-wise this could be too inefficient or untenable. Rather, the key is for the above mentioned operational managers and system managers at the system-level to be made accountable to higher-level operational and technical authorities who oversee the development and realisation of SoS-level capabilities. Assuming such reporting structures and relationships are achievable for a particular nation desiring to develop coherent SoS capabilities for her military defence, the next level of details in terms of the scope of individual roles and responsibilities and the process can be worked out.

Based on this assumption, this paper examines the key considerations required in architecting SoS capabilities for a nation's military defense enterprise and proposes a systems approach to integrate the dimensions of people and process.

KEY CONSIDERATIONS

There are at least five key considerations required in architecting SoS capabilities for a nation's military defense enterprise.

The first consideration is mission orientation. For each SoS, we need to relate it to a large-scale operational mission such as maritime security. In such a mission, systems and personnel from diverse domains or military Services may be required. For the example of maritime security, specific airborne surveillance platforms from the air force may be required to complement patrol ships from the navy. A mix of manned platforms and unmanned platforms may be employed to collectively reap the benefits of human decision-making in complex situations, mission persistence and risk-minimization to human lives. For convenience of discussion in this paper, the term “**Mission SoS**” will be used to describe an SoS that directly fulfills a large-scale mission’s objectives and is composed of multiple heterogeneous systems that span across functional domains or military Services. Another example of a Mission SoS is an integrated air defense SoS that employs fighters, surface-to-air missiles, airborne surveillance platform and naval ships [Tan et al 2008].

A second consideration is the finite supply of non-scalable resources shared across various Mission SoS. Examples of such resources are electromagnetic spectrum (EM) bandwidth, airspace or deployment sites demanded by the various systems. Without coherent allocation of these finite resources to various Mission SoS, conflict in resource usage may occur should two or more Mission SoS be required to operate in temporal or spatial proximity. This could lead to critical modes of failure in an SoS. For further discussion in this paper, the term “**Enterprise Resources**” will be used to describe such finite shared resources.

A third consideration is to achieve some level of commonality and synergy in scalable technological solutions to be used in various Mission SoS. Examples of such solutions are communications solutions (e.g. WiMax, WiFi) or interoperability standards (e.g. network routing protocol) to be applied across various Mission SoS, and common aerial platform types to support various operational tasks found in different Mission SoS. Without a holistic effort to establish such “common denominators” in technological solutions across various Mission SoS, the implemented technological solutions for each Mission SoS may be optimal for the individual SoS but sub-optimal at the enterprise level. For C4 systems, this could mean sub-optimal enterprise interoperability. For other cases, this could mean sub-optimal economies of scale in terms of cost and human resource utilization. For further discussion in this paper, the term "**Enterprise Technology**" will be used to describe such technological solutions.

A fourth consideration is that the efforts by various personnel to architect these Mission SoS, Enterprise Resources and Enterprise Technology may not be sequential but concurrent. This creates complexity in synchronizing these efforts at any one time due to the dependencies.

A fifth consideration is uncertainty factors in view of the potentially long implementation time for Mission SoS. There is a need to consider logical time frames or spirals of how Mission SoS would transit from "as-is" to "to-be" states in the face of uncertainties in dimensions of technology, threat scenario, operational environment etc.

OVERVIEW OF SYSTEMS APPROACH

Given the five key considerations aforementioned, the following approach is proposed with the intent to architect coherent SoS capabilities for the nation's military defense enterprise. This approach encompasses the scope of work ("what to do"), technical organization structure ("who to do what") and process ("when to do what").

SCOPE OF WORK

Architecting needs to be done for each Mission SoS, Enterprise Resource and Enterprise Technology to achieve coherence. Architecture analysis will be used support the evaluation of architecture alternatives. After the architecture for a Mission SoS is established, master planning needs to be done to factor in implementation spirals in the face of uncertainty over an extended time horizon.

TECHNICAL ORGANIZATION STRUCTURE

The national technical agency responsible for the architecting and implementation of the SoS capabilities must structure her human expertise resources accordingly. Various architects and SoS Implementation Managers are key personnel that must be identified on top of project managers of individual constituent systems.

The types of architects required are the SoS Architect, the Resource Architect and the Technology Architect. These 3 types of architects would be respectively responsible to architect Mission SoS, Enterprise Resources and Enterprise Technology. To support the overall mission requirements in the military defense enterprise, there would be several architects in each of the 3 architect types. Re-using examples aforementioned, there could be

- SoS Architect (Maritime Security), SoS Architect (Integrated Air Defense)
- Resource Architect (EM spectrum), Resource Architect (Airspace), Resource Architect (Deployment Sites)
- Technology Architect (communications solutions), Technology Architect (aerial platforms)

The aforementioned architects may require specialized personnel to provide rigorous quantitative analysis when evaluating gaps and architecture alternatives for Mission SoS. An Architecture Analyst would provide such analysis. It is desirable for a common Architecture Analyst to support the analysis needs for the entire enterprise. This will address the dependencies across analyses and provide consistency in analysis tools and methods.

Once the architecture is determined, an SoS Implementation Manager will perform the SoS capability master planning and implementation oversight for each Mission SoS. This will facilitate coherent implementation of constituent systems by the various system managers.

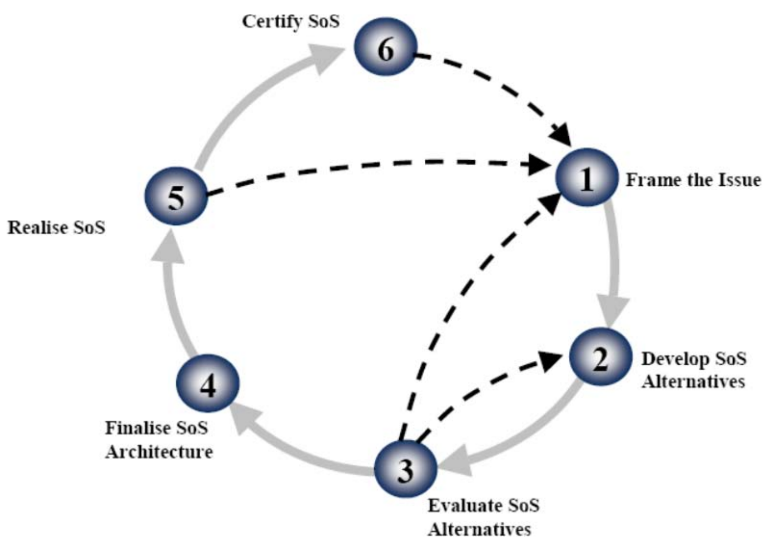
PROCESS

Architecting is said to be both an art and a science [Maier & Rechtin 2000, Tan et al 2008]. On being an art, it relies significantly on intellectual discussions with key stakeholders to derive innovative ideas and solutions. As a result, any process that is written to guide architecting should not be overly dogmatic or algorithmic since this would stifle creativity and "out-of-the-box" concepts. Nevertheless, there needs to be broad phases that describe the process and guidelines on key activities that ought to be conducted.

In this light, the following paragraphs highlight the broad phases and process guidelines on key activities when architecting. Although the phases are sequenced in a broad chronological order, in practice they will likely not be executed in a strict "waterfall model" sequential fashion. Rather, iterations across specific phases can be expected. This iterative nature is also contributed by the dependency between the architecting of various Mission SoS and the architecting of Enterprise Resources and of Enterprise Technology that support across various Mission SoS.

Generic Process & Phases

The figure below shows a generic process that includes the major elements required of architecting. It adopts a life cycle perspective and is developed with simplicity and flexibility in mind to cater to different levels of applications from product, systems, capability and enterprise. It consists of 6 broad phases and is iterative in nature.



A brief description of these 6 broad phases is as follow:

- **Frame the issue –** This phase will facilitate the involvement of necessary stakeholders so that the right issues are addressed. This will require an examination of strategic, operational and technical perspectives to gain a deeper understanding of the matter in hand. Any capability gaps will be identified at this step.

- **Develop SoS Alternatives** – This phase is to generate a broad range of alternative SoS architectures to address the capability gaps. The emphasis is on the exploration of the solution space in terms of alternative concepts of operations (CONOPS), technology, resource usage, or a mix of these.

- **Evaluate SoS Alternatives** – This phase involves the evaluation of the set of SoS alternatives. The evaluation metrices and measurement framework to compare the alternatives need to be established.

- **Finalize SoS Architecture** – The output of architecting is an endorsed SoS architecture. This phase involves the documentation of this architecture and the development of SoS capability master plans to chart the SoS implementation and capability realization milestones.

- **Realize SoS** – This phase will involve various project teams responsible for the acquisition and development of various constituent systems based on the SoS architecture and capability master plan.

- **Certify SoS –** Verification, validation and certification of the SoS are involved during this phase. In general, verification is a quality process to ensure that the SoS complies with specification. Validation is the process to establish a certain degree of confidence that the SoS accomplishes its intended mission capabilities and addresses user needs articulated in phase 1. Both aspects are essential as verification ensures that "we built it right" while validation ensures that "we built the right thing".

The iterative nature of the architecting process is expected as the realization of an SoS may span many years. Hence, changes in the external environment or earlier assumptions may warrant a need to re-examine the SoS architecture. The dotted arrows represent the need to refer back to the earlier phases to verify and evaluate the SoS when necessary.

The following sections elaborate on phases 1 to 4 of this generic process, including guidelines, in the context of architecting SoS, Enterprise Resources and Enterprise Technology.

Process Guidelines When Architecting A Mission SoS

Frame the Issue (Establish the SoS' Mission Requirements) – This phase will be predominantly led by the military stakeholders. The SoS architect's key role is to understand and clarify the high-level operational requirements and mission objectives of the SoS. For an existing SoS that is already operationally deployed, this phase aims to review the impact of any changes in the SoS' operating environment and threat scenarios. Significant changes may necessitate a review of the SoS' mission objectives. For a fundamentally new operational environment or threat scenario, there may be no existing SoS or even collection of disparate systems to address it. In such a case, specific military stakeholders will need to define the future SoS' mission objectives.

Frame the Issue (Assess if the SoS has Capability Gaps) – Having clarified the SoS' mission objectives, the ability to fulfill them needs to be assessed. This could be done qualitatively by the SoS Architect or quantitatively with the support of the Architecture Analyst. When the mission objectives cannot be satisfactorily fulfilled, alternative CONOPS could be explored without changing the existing set of systems, connectivity schemes and technology solutions that constitute the SoS. Examples would be modifying constituent systems' rules of engagement or roles under specific threat scenarios. Should these alternative CONOPS yield satisfactory outcomes, the existing SoS would be considered as adaptable and may require no further changes. Otherwise, a capability gap exists and the subsequent architecting phases will be required.

Develop SoS Alternatives – Once the capability gaps have been identified, the SoS architect will address these gaps. This could involve exploring further changes in the SoS' CONOPS or exploring changes in its technology components. Based on these changes, various SoS alternatives would be formulated. Both legacy systems and new systems will be factored in.

For SoS alternatives requiring changes in CONOPS, the SoS architect needs to co-develop this with specific military stakeholders of the SoS. There are two broad categories of such changes, namely redefining of SoS boundaries and redefining connectivity requirements within the SoS.

For SoS alternatives requiring changes in technology components, the SoS architect should identify these changes holistically with the Technology Architects. This aims to promote reuse, consistency and economies-of-scale in implementing similar classes of technology solutions across different SoS in the nation's military defense. However, this may not be straightforward as specific technology release policies may inhibit the implementation. For example to implement a common enterprise-wide technology component in a specific SoS, certain constituent systems may be unable to incorporate this component. This could be due to proprietary restrictions that inhibit the release of technical information between different defense contractors. Where possible the SoS architect should surface such issues early and conceive the possible workarounds or alternatives. Nonetheless the SoS Architect should not dwell into details that can only be addressed during SoS implementation. In cases where technology solutions required are unique to the SoS, the SoS architect should consider a broad class of solutions rather than narrow down to a single specific solution at this stage. Overall, this broad exploration of alternatives in technology components aims to provide flexibility for the SoS Implementation Manager in the downstream capability implementation.

The above changes in CONOPS or technology components may be subject to further constraints in terms of finite enterprise resources shared across various SoS. For example, the ability to increase network connectivity within an SoS or to utilize specific communication systems may be constrained by limited EM spectrum bandwidth that could be allocated to this SoS. To factor this, the SoS Architect needs to consult the relevant Resource Architects to check if there are any such concerns up front, based on the Resource Architects' broad assessment.

A key characteristic of an SoS is evolutionary development [Maier 1996], where constituent systems of the SoS are introduced or replaced over time. In generating SoS alternatives, the

SoS architect should depict what the broad SoS configuration would be at specific logical threat scenario timeframes or technology spirals. Techniques such as Real Options thinking [de Neufville 2002] could be employed here to bring clarity.

When all the required SoS alternatives have been generated, it would be useful to consolidate these alternatives into one or more SoS architectures. A SoS alternative will generally encompass both the SoS architecture and the broad SoS configuration. While the SoS configuration will evolve over timeframes or spirals, the underlying SoS Architecture could be enduring. This will help to finalize the appropriate SoS architecture subsequently after the alternatives have been evaluated.

Evaluate SoS Alternatives – The Architecture Analyst will evaluate the SoS for mission performance in the relevant timeframes via means such as operational analysis (OA) and modeling and simulation (M&S). The Architecture Analyst should also evaluate other qualities of the Mission SoS to address the intrinsic resilience of the SoS to uncertainties over an extended time horizon into the future. These qualities are known as "ilities" [McManus, Richards, Ross and Hastings] such as flexibility, adaptability, robustness etc. Real Options valuation [de Neufville 2002] techniques may be considered to evaluate flexibility. Finally, the Architecture Analyst needs to formulate an evaluation framework to holistically integrate the metrices for performance and "ilities", with inputs from the SoS Architect. As the Architecture Analyst will evaluate different Mission SoS over time, there should be a good knowledge management system to capture the models and analysis dependencies that will accumulate over time.

At the end of the evaluation, the SoS architecture of the Mission SoS will need to be finalized with the relevant stakeholders based on acceptable SoS alternatives. The key here is "acceptable" rather than "optimal". This thinking acknowledges the various uncertainties to be faced in the SoS implementation, such as timely maturity of technology currently in R&D, threat scenario evolution, export control constraints etc. It places premium on preserving the flexibility to adapt to these uncertainties. This aims to avoid situations during SoS implementation where the SoS cannot be fully implemented because acceptable options were prematurely ruled out while the remaining optimal option cannot materialize due to external factors such as R&D failure or the inability to acquire specific technology.

Before finalizing the SoS Architecture, the SoS Architect needs to verify with the Resource Architects and Technology Architects that the shared requirements are still valid or supportable, in case assumptions had changed due to updated demands from other SoS architects. Where changes are significant, "Evaluate SoS Alternatives" or even "Develop SoS Alternatives" may need to be revisited.

Finalize SoS Architecture – The recommended SoS architecture would be described using established architecture description frameworks such as DoDAF. The SoS Architecture will then need to be endorsed jointly by the relevant military and technology stakeholders. Once endorsed, the Resource Architects and the Technology Architects will register the new requirements placed on their respective areas by this SoS. Thereafter, the SoS Implementation Manager plays the key role, building upon the work established by the SoS Architect. The SoS Implementation Manager will develop the details on when projects for constituent systems need to be initiated and integrated so as to realize the various capability spirals. The SoS Implementation Manager also needs to develop the strategies to acquire or develop the constituent systems, in which he will consult the relevant Technology Architects for systems using Enterprise Technology.

Realize SoS – The above work established by the SoS Implementation Manager will coherently guide the system managers who implement the various constituent systems in the following phase “Realize SoS”. In this realization phase, there may be cases of significant changes in system performances that can be achieved when specific solutions are chosen and implemented. These findings will be used by the SoS Architect to review the phase “Frame the issue”. The SoS Architect will need to assess if the original large-scale mission capability could still be met. Any significant changes may require developing evaluating new SoS alternatives and determine the mitigating action. The SoS Architect will work closely with the SoS Implementation Manager on this. An example could be that the SoS Implementation Manager may need to upgrade performance requirements of a specific system that has not been implemented yet, so that this new system could compensate certain capability shortfalls at the SoS level.

Process Guidelines When Architecting Enterprise Resources

Phases 1 to 4 of the generic architecting process could also be applied for Enterprise Resources and Enterprise Technology. While further details need to be rationalized, the preliminary guidelines are as follow:

Frame the Issue – The Resource Architect will need to have a broad understanding of mission requirements of each Mission SoS. Use of the Enterprise Resource by legacy systems and committed projects will need to be captured as firm demands. The Resource Architect will also need to assess the global availability of his Enterprise Resource for military usage based on competing demands from national civil agencies or even multi-national agencies (e.g. EM spectrum, airspace).

Establish the Initial Architecture – With the above information, the Resource Architect will develop a roadmap of available “white space” for the Enterprise Resource over time. However, the Resource Architect may be unable to develop concrete alternatives to allocate the Enterprise Resource to various Mission SoS when demands are not clear yet. Nonetheless, the roadmap of “white space” will serve as an initial architecture. This will enable the Resource Architect to meaningfully interact with the SoS architects when they develop SoS alternatives.

Iteration – Whenever a particular SoS Architect has finalized an SoS Architecture, the requirements on Enterprise Resource will be used to update the Enterprise Resource roadmap. More concrete demands will be placed when the SoS undergoes implementation, and feedback to the Resource Architect will be necessary. As more concrete demands accumulate with time, the Resource Architect will use the information to develop alternative allocation schemes for various SoS. Evaluation of alternatives could be to assess the performance trade-off of the various SoS when allocated with alternative resource allocation schemes. Senior military stakeholders will likely have to decide on the course of action given such trade-off.

Process Guidelines When Architecting Enterprise Technology

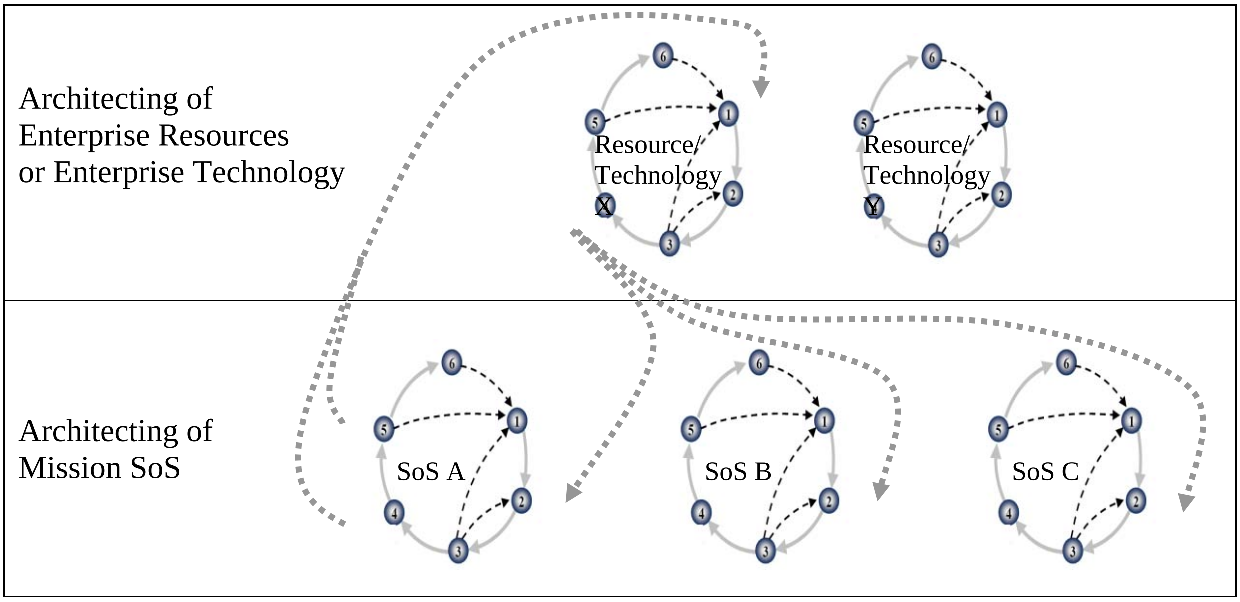
The key guidelines for the Enterprise Architect are similar in nature to those for the Resource Architect. These would include obtaining a broad understanding of mission requirements of each Mission SoS and a corresponding broad assessment of demands on his Enterprise Technology. The Technology Architect will need to assess the mainstream technology trends of his Enterprise Technology including relevant trends in the civilian sector (e.g. IT, networking) and develop a roadmap of technology evolution and obsolescence management over time. This will enable the Technology Architect to meaningfully interact with the SoS architects. Likewise the Technology Architect will need feedback from the implementation of constituent systems in "Realize SoS" phase of architecting the Mission SoS.

SUMMARY

The table below summarizes the process guidelines to architect a Mission SoS, using two generic Mission SoS (A and B) to illustrate the inter-relationships between the SoS Architects, the SoS Implementation Manager, the Resource Architects, Technology Architects and Architecture Analyst.

Activities to architect an SoS	Technical lead for SoS A	Technical lead for SoS B
Establish the operational environment, threats and mission objective for this SoS	Not applicable (military stakeholders only)	Not applicable (military stakeholders only)
Establish the existing capability gap of this SoS	SoS Architect (SoS A),	SoS Architect (SoS B),
	supported by Architecture Analyst	
Develop SoS alternatives (across required time frames) via redefining	Overall – SoS Architect (SoS A)	Overall – SoS Architect (SoS B)
SoS boundaries (and roles of platforms)	SoS Architect (SoS A)	SoS Architect (SoS B)
Connectivity requirements for platforms	SoS Architect (SoS A)	SoS Architect (SoS B)
Application of specific Enterprise Technology	Various Technology Architects	
Utilization of specific Enterprise Resources	Various Resource Architects	
Evaluate SoS alternatives	Architecture Analyst, in consultation with	
	SoS Architect (SoS A)	SoS Architect (SoS B)
Finalize SoS architecture based on acceptable SoS alternatives	Overall – SoS Architect (SoS A),	Overall – SoS Architect (SoS B),
	in consultation with Resource Architects, Technology Architects	
Establish SoS implementation road map based on	Overall – SoS Implementation Manager (SoS A)	Overall – SoS Implementation Manager (SoS B)
SoS architecture and SoS capability spirals	SoS Architect (SoS A)	SoS Architect (SoS B)
Acquisition or development strategy for constituent systems	SoS Implementation Manager (SoS A) and Various Technology Architects	SoS Implementation Manager (SoS B) and Various Technology Architects
Decision points for constituent systems (e.g. project initiation date, integration date)	SoS Implementation Manager (SoS A)	SoS Implementation Manager (SoS B)

Referring back to the generic architecting process mentioned earlier, the figure overleaf illustrates the key interdependency between the architecting of Mission SoS with the architecting of Enterprise Resources and Enterprise Technology. The feedback loops across the architecting of Mission SoS and "enterprise resources/technology" highlight that regular dialogue between the various architects is required. When conceiving SoS alternatives in phase 2 of the generic process, SoS Architects should consult the Resource Architects and Technology Architects on the possibilities and constraints. When SoS architecture is finalized or the SoS is being implemented (phases 4 and 5), the relevant information must be channeled back to the architecting efforts of the Resource Architects and Technology Architects, where they would re-assess the key issues such as the emergence of gaps. The feedback loops are expected to be recursive over time.



CONCLUSION

With impetus to attain "global optimum" for SoS capabilities, the aspect of managerial challenges were highlighted. Based on the assumption of an effective "top-down" leadership to establish organizational structures that will mitigate "stove-piped" system requirement definition and implementation, the key considerations to bring clarity in architecting SoS capabilities were described. Cognizant of these considerations, an approach to architect and implement coherent SoS capabilities was described, addressing the dimensions of scope of work, people and process. The approach attempts to weave in the considerations of limited shared resources and common technological solutions across the national defense enterprise into the process of architecting an SoS that would fulfil a large-scale mission capability.

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Biography

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