

Systems of Systems Considerations for the Engineering of Systems

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ABSTRACT

This paper addresses the Systems of Systems (SoS) considerations that are recommended for systems engineering of systems based on a guide recently produced by The Technical Cooperation Program¹. While it is recognized that most military capabilities are generated by systems of systems working together effectively, in most nations, defence organizations acquire military systems on a system by system basis. This paper addresses the need to ensure SoS considerations are addressed throughout the system development life cycle to ensure that systems, when deployed, can effectively operate in a SoS context to support desired capability objectives. It describes the types of SoS considerations important to the engineering of systems and reviews the key considerations applicable to critical points in the SE development process. The paper concludes with a discussion of the need for a SoS technical base to support the engineering of systems.

1.0 INTRODUCTION – WHY ADDRESS SoS CONSIDERATIONS FOR SYSTEMS?

Despite the fact that almost all current military capabilities require coordinated operation of multiple independent systems or Systems of Systems (SoS), today most military system acquisitions operate on a system by system basis. User requirements are posed in terms of a particular capability gap and are then typically translated into requirements for a new or upgraded system. Further, SoS are typically composed of existing systems which are identified to address new or emerging user needs, often while these systems continue to support original users. As a result, SoS evolution is typically based on changes in constituent systems or the addition of new systems, making these systems the essential building blocks of SoS, as shown in Figure 1.



Figure 1: Building Blocks of Systems of Systems.

¹ The Technical Cooperation Program, “*Recommended Practices: Systems of Systems Considerations in Engineering Systems*” Technical Report TR- JSA/TP4-1-2014, August 2014. <http://www.acq.osd.mil/se/docs/TTCP-Final-Report-SoS-Recommended-Practices.pdf>, Accessed 11 26/2014.

Unless the implications of the SoS context are considered early and throughout acquisition of a system, there can be significant risk to the effectiveness and successful fielding of the system to meet user capability needs. Recognizing this, a technical panel of The Technical Cooperation Program has recently released a guide entitled “Recommended Practices: Systems of Systems Considerations for the Engineering of Systems”². This paper is based on the material presented in this guide.

2.0 TTCP TP-4 RECOMMENDED PRACTICES FOR SoS CONSIDERATIONS FOR SYSTEMS

2.1 The Technical Cooperation Program (TTCP)

The Technical Cooperation Program (TTCP) is an “international organization that collaborates in defence scientific and technical information exchange; program harmonization and alignment; and shared research activities for the five nations.”³ The US, UK, Canada, Australia and New Zealand are the partner nations in TTCP. The US, UK, Canada, and Australia are active participants in the TTCP Technical Panel 4 (TP-4): “Systems Engineering for Defence Modernization” of the Joint Systems Analysis (JSA) Group.

As part of its work program, TP-4 hosts a SoS Workstream which provides a forum for national technical expertise in SoS that offers opportunities for peer review, technical exchange on approaches to common problems not otherwise available and enables each nation to better address challenges informed by broader experience of their national colleagues. The TTCP guide on recommended practices for SoS consideration in system development is a product of this workstream.

2.2 Recommended Practices Guide

Based on the collective experiences across the US, UK, Canada and Australia, a set of recommended practices has been developed to address the key SoS considerations in the engineering of defence systems.⁴ This guide provides a tool for systems engineers and acquisition programs to ensure that systems will be able to operate effectively in the SoS environment where they will be employed to support user capability needs, avoiding unnecessary rework and cost.

As is shown in Figure 2, the guide is structured around ISO 15288 lifecycle stages as the framework for presenting the recommended practices, with a focus on key points in development. The guide is structured as a series of tables focused on each of the selected review points: Initial Review, Alternatives Review, Requirements Review, Design Review, and In-Services Review(s). In some acquisition and engineering processes, these are formal review points, but in all cases these are logical points in development to review the maturity of the system and to assess progress before moving forward in development.

² Ibid.

³ The Technical Cooperation Program, <http://www.acq.osd.mil/ttcp/>, Accessed 11/26/2014.

⁴ The Technical Cooperation Program, “*Recommended Practices: Systems of Systems Considerations in Engineering Systems*” Technical Report TR- JSA/TP4-1-2014, August 2014. <http://www.acq.osd.mil/se/docs/TTCP-Final-Report-SoS-Recommended-Practices.pdf>, Accessed 11 26/2014.

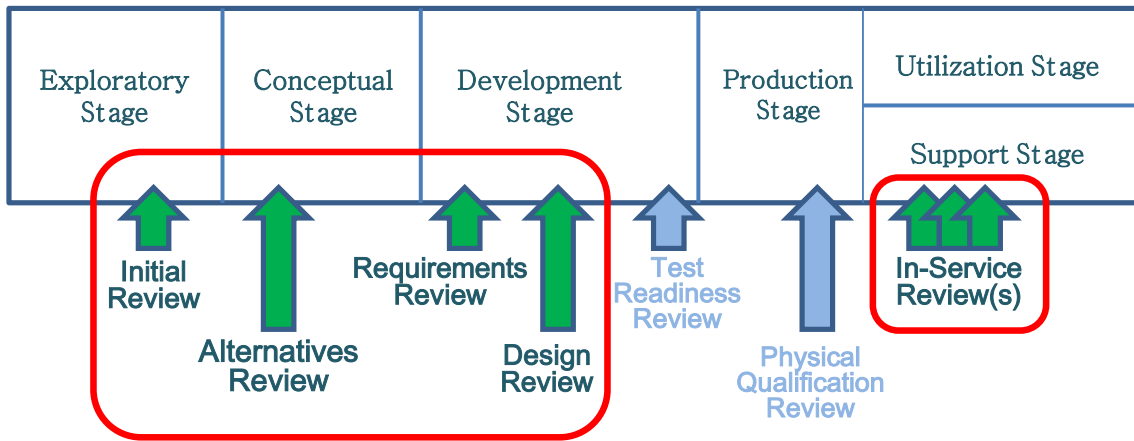


Figure 2: ISO 15288 Lifecycle Stages and Selected Review Points for SoS Considerations Guidance⁵.

The guide itself is organized as a set of structures tables, as shown in Figure 3, which highlights how the system context for the SoS considerations is established for each review point.

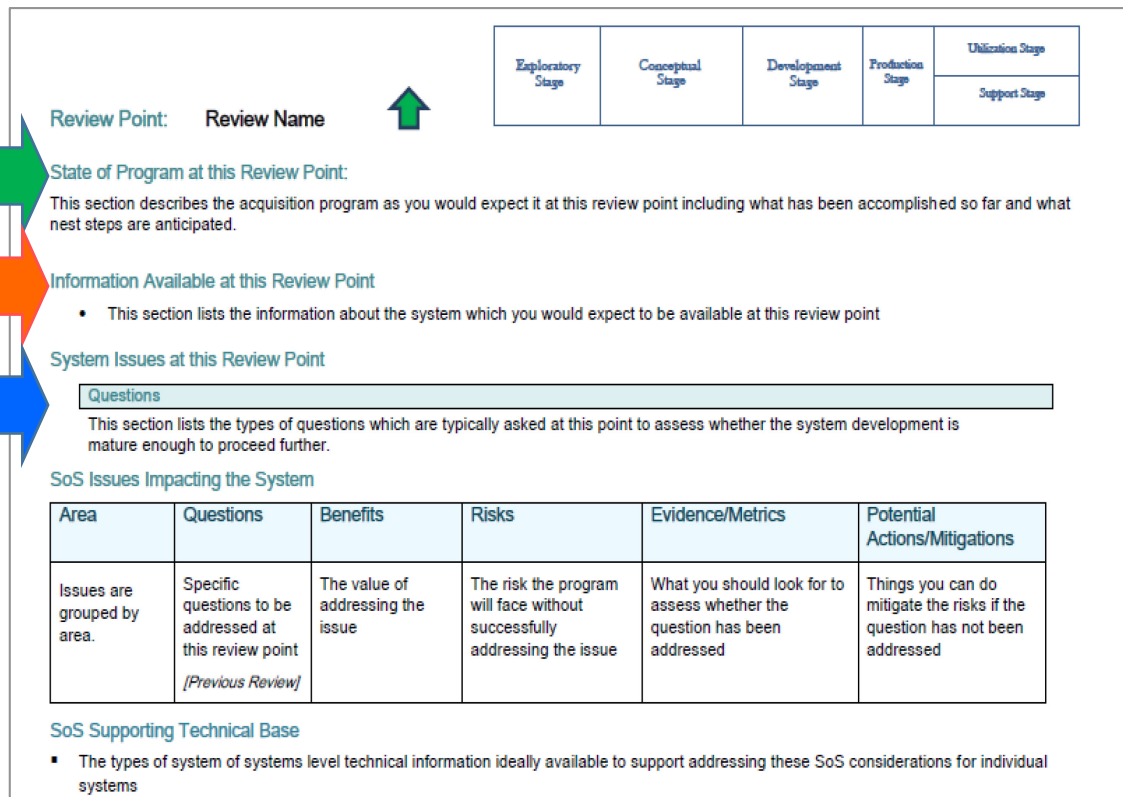


Figure 3: System Context for Each Review Point.

In particular, the table for each review point includes a discussion of the “State of the Program” (Figure 3, green arrow) at the review point, laying out what would be expected of an acquisition program at this review point, in particular, those activities which have been completed and the next activities anticipated in

⁵ Ibid.

development of the system. Each table also includes a listing of the “*Information Available at This Review Point*”, outlining the information expected to be available for the system reflecting its stage of development (Figure 3, orange arrow). Finally, each table includes a description of the “*Systems Issues at This Review Point*” (Figure 3, blue arrow) where the table presents the typical questions used to assess system maturity at that review point.

Having set the context for the system developing at the review point, the tables then focus on the core content of the guide, the “*SoS Issues at this Review Point.*” (See Figure 4) The SoS issues are categorized into four areas: capability, technical, management and cost (Figure 4, white arrow). These are discussed in the next section of this paper. SoS issues are formulated in terms of “*questions*” (green arrow) which should be addressed when reviewing systems at each review point. For each question the “*benefit*” to the system (orange arrow) of addressing these SoS questions are described, as are the risks associated with failing to successfully address the SoS questions (blue arrow). The type of “*evidence*” expected for this question is provided (purple arrow), identifying the information or artifacts that provide the data needed to address the questions. Finally, the table includes possible “*mitigating*” actions when the questions are not satisfactorily addressed (yellow arrow).

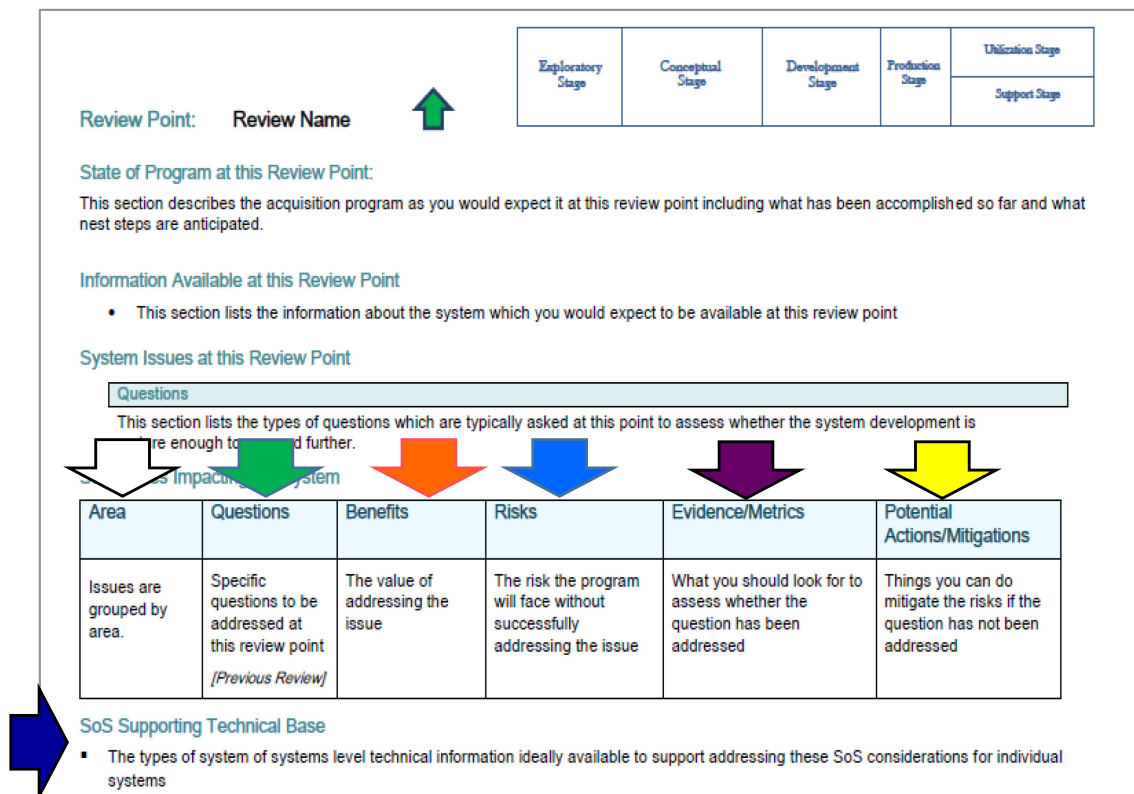


Figure 4: SoS Content of Tables for Each Review Point.

2.3 Types of SoS Considerations

The guide to SoS considerations addresses SoS-related issues in four areas.

The first area addresses “*Capability*” considerations, asking the questions:

- Have the impacts of the end to end user capability needs for the system been considered in the system concept, requirements, design and system upgrade?

- Has the role of other systems supporting the capability been factored into the technical planning and design of the system?

In the second area, “*Technical*” considerations are addressed, including:

- Have the impacts of the role of the system in the system of systems been considered in the technical requirements and design?
- Have the interfaces and constraints of other systems (e.g. platform) been considered in the technical design?
- Are changes in other systems going to be needed? Are these technically feasible?

The third, “*Management*” area, addresses questions such as:

- Have management agreements been made to work with other systems to ensure that technical interfaces and interdependencies are addressed and managed over the development?

Finally, in the fourth area, “*Cost*” considerations concerning resource planning are addressed, including:

- Have plans been made to fund the SoS requirements for both this system and others?

Inclusion of these four areas is based on the recognition that technical issues are important but there can be other SoS implications in areas of program planning, management and resources, as well as considerations associated with the user context for the system.

3.0 SoS CONSIDERATIONS AT KEY POINTS IN SYSTEMS DEVELOPMENT

3.1 Overview

In the next section, the key SoS considerations for each of the review points will be summarized based on the materials in the TTPP recommended SoS considerations guide.

3.2 Initial Review

The first review point is called the “Initial Review” (Figure 5). This review point occurs during the initial exploratory phase of system development.



Figure 5: Initial Review Point.

At this stage, typically a capability gap or need has been identified by users and a range of potential approaches to filling the gap has been identified. The decision to be made at this is point is whether there is sufficient understanding of the need and available technically viable options to commit to proceeding to formally explore alternatives for addressing the need. The information typically available includes a description of the need and the options available for fulfilling the need.

The SoS *capability* considerations at this point include questions pertaining to the degree of understanding of the operational context for any proposed new development. In particular⁶:

- Has the operational context of the capability gap been described?
- Have operational context constraints on the candidate solutions been identified?
- How would any new system which might address the gap fit into current operations?
- If a new system were to be considered, have interfaces with or required changes to current/legacy systems or infrastructure been identified (both national and coalition)?
- Have non-material approaches and been considered?

These are important initial user considerations, since if the operational context for any new development is not addressed early in the development process, decisions may be made that lead to systems which do not adequately operate in the designated user environment.

There are *technical* considerations which apply at this early stage as well, in particular:⁷

- Have the external stakeholders or external systems/infrastructure affected been identified? This includes both systems/services on which the new or upgraded system depends as well as systems/services that depend on the new or upgraded system.
- Is there an understanding of the ability to influence resource changes in associated systems, infrastructure, or non-material factors?

From a *management* perspective, it is important to understand whether the new systems will be part of a recognized SoS activity and if so, whether there has been discussion with the management of that SoS over the development of any new system, including what formal management arrangements have been made with the SoS for the new systems development process.

Finally, what *technical data about the larger SoS* supported by the new system development would ideally be available at this stage to provide the basis for addressing these questions? Ideally, analysis has been conducted to provide needed context, including that based on established end-to-end capability objectives, performance metrics and current performance data. Ideally, there would be an understanding of the systems currently supporting those objectives (technical baseline, gaps, etc.) including an understanding of how systems currently support the capability (including functionality, performance, interfaces, data exchanges etc.) as well as the current concept of operations – how the systems are employed by users in an operational setting to deliver the capability objectives. Note that the availability of the SoS technical data is an ideal case and, as will be discussed, it is often the situation that this data is not readily available to the system developer and engineering team. However, whether or not the SoS data are available, the system faces the same risks and it is important to address the SoS considerations in all cases.

3.3 Alternatives Review

The second review point is the “Alternatives Review” (Figure 6). This review point occurs during the Conceptual Stage of system development.

⁶ Ibid. “Initial Review” Table.

⁷ Ibid. Initial review table.

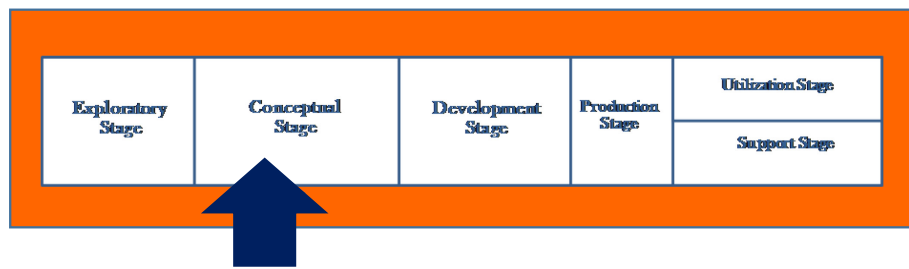


Figure 6: Alternatives Review Point.

Typically at this point in development a decision has been made to investigate a material acquisition to address a user need, alternative approaches to addressing the need have been analysed and a preferred approach has been identified. By this point, there is a good understanding of how users will conduct the operation and use the new system in this context, of the nature of the user needs, and of the constraints on any new system. The results of the analysis of alternatives provide the basis for initial plans for systems engineering and for system test and evaluation, as well as for the strategy for technology development.

What are the SoS considerations at this point?

First, from the perspective of the user *capability*, it is important to be sure that the SoS context for the capability is clear, factoring in any changes from the last review point. Operational context constraints on the candidate solutions and the relationship with the other systems supporting the capability have been considered, and these have been communicated to these systems. By this point interfaces with other systems in development or planned systems have been identified, as well as any required changes to these other systems. Further, the benefits from and for other systems or infrastructure, both national and coalition, have been identified, along with any impacts on non-material factors.

From a *technical* perspective, by this point, technical constraints on the system imposed by the SoS context for the system have been identified and considered in selecting the system solution. This includes physical (e.g. size, weight, cooling, power limits) and electronic requirements (e.g. signature, interference, etc.), as well as impacts on information exchange and management (e.g. network, bandwidth, information needs, etc.) and on safety, security and information assurance. The dependencies and interfaces for the system have been identified, defined, and controlled.

Finally from a *management* and *cost* perspective, if the new system will support a recognized SoS, it is important that formal management arrangements have been established and implemented between the program and the SoS, arrangements which address both schedule and budget. If there is no recognized SoS, comparable arrangements need to be made with other systems where there are dependencies with the new system.

The same *SoS supporting technical data* discussed in the initial review would ideally be available for this review, as well. This includes established end-to-end capability objectives, performance metrics and current performance data, a good understanding of the systems now supporting the SoS under the current concept of operations, as well as the overall SoS technical baseline.

3.4 Requirements Review

The third review point is the “Requirements Review” (Figure 7). This review occurs later in the Conceptual Stage of the system lifecycle.

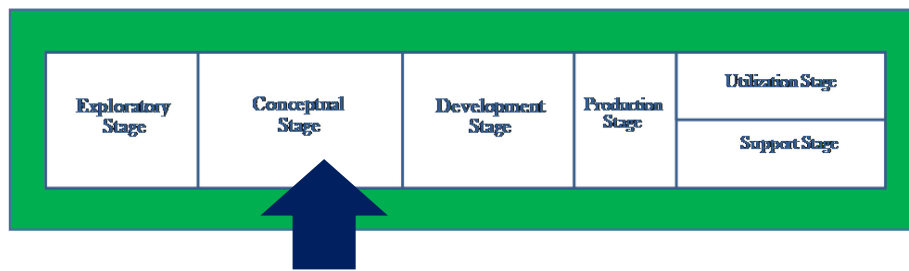


Figure 7: Requirements Review Point.

By the *requirements review point* the preferred solution has been selected, an in-depth review of user needs has been conducted, and the system requirements have been documented. Typically by this point in development, there is an updated understanding of how users will conduct the operation and use the new system, a full definition of the environment as well as functional and systems requirements, and an initial system architecture. The plans for systems engineering and test evaluation have been updated and plans have been made for risk management, for source selection, and for safety, security, and supportability.

The SoS considerations for the system at this point in development include a review of the *capability* issues addressed in the earlier reviews to ensure that there is a clear understanding of the use SoS context. Operational context constraints on the candidate solutions have been identified along with the relationships with the other systems supporting the capability and which have been communicated to these systems. Interfaces with other systems in development or planned systems have been identified, as have any required changes in those systems. Again, here, benefits from and for other systems or infrastructure have been identified, both national and coalition. Finally, any impact on non-material factors have been updated and addressed.

From a *technical* perspective, constraints on the system imposed by the SoS context identified in the prior review are reassessed and considered in selecting the system solution. This includes physical requirements, electronic and information exchange/management requirements, as well as safety, security and information assurance.

Finally, the same *management and cost* issues are reviewed to be sure that the requisite arrangements have been established and implemented with relevant SoS organizations or if there are no recognized SoS, then with the systems directly.

The same SoS technical data is needed for this review as the previous reviews; that is an understanding of the composition and performance of the current baseline of systems of systems supporting the user capability addressed by this system.

3.5 Design Review

The fourth review point is the “Design Review” (Figure 8) which occurs at the outset of the Development stage in the system life cycle.

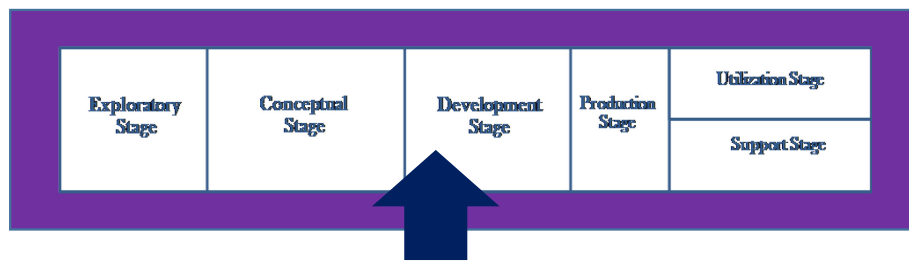


Figure 8: Design Review Point.

At this point in development, the designs (preliminary or detailed) for the system have been completed. There is an established system allocated baseline and program risk assessment. Planning for long lead time items has begun, as has planning for life cycle support, security, program protection, anti-tamper, and safety. The system cost analysis and schedule have been updated, information on certification and accreditation have been assembled and the grounds of user acceptance have been established.

SoS Considerations at this stage include a review of the *capability* considerations to ensure that the designs are based on an updated description of how the users will conduct the operation, how they expect to use the new system in this context, and in the user statement of need, reflecting any changes.

From a *technical* perspective, constraints on the system imposed by the SoS context are addressed in the design as are the SoS-derived technical requirements and resulting interfaces. For *technical management considerations* which involve interactions with other systems, **design features need to be negotiated** with the others involved. Any internal interfaces which may need to be exposed in the future to support evolving SoS needs have been identified. Technical trade-offs made for this system have considered impacts on the SoS/mission thread or system coherence with the broader system (enterprise).

Finally, the same management and cost considerations addressed in earlier reviews again apply here. If the system will support one or more recognized SoS, management arrangements need to be established and implemented with the organization responsible for the SoS(s). If there is no recognized SoS, similar formal arrangements have been made with the other system. At this review point it is important to ensure that SoS-related system *costs* been identified and included in cost estimates, including costs of requirements identified and added since system costing was initially estimated, such as costs to integrate a new system onto a platform.

Ideally at this review point in terms of *SoS supporting technical data* a SoS architecture would be employed as the framework for understanding how the system will support the capability (including functionality, performance, interfaces, data exchanges etc.) and interdependencies among systems and non-material aspects of the supporting capability should be fully evaluated and assessed. Again, ideally, the SoS architecture artifacts would be part of preliminary and formal design reviews for this system.

3.6 In-Service Review(s)

The final review point is the “In-Service Review(s)” (Figure 9) which occurs after the system is deployed during the support and utilization stages of the lifecycle.

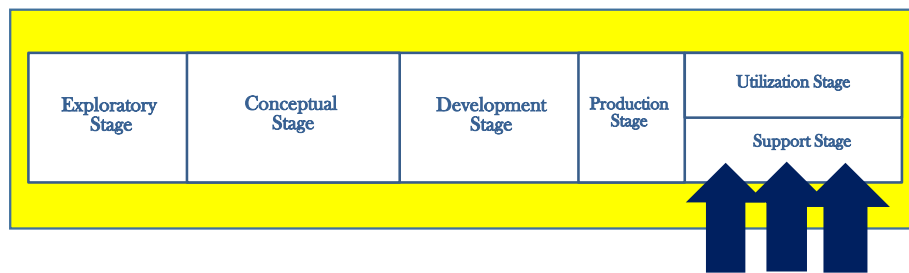


Figure 9: In-Service Reviews.

At this point the system has been fielded and is in operation and support. The in-service review addresses how well the system is delivering the capability to the user and how well the system is positioned to meet future operational scenarios. The in-service review is based on various types of information, including operational testing results, user feedback on systems performance during both exercises and operations, on field and maintenance reports, and in-service operation and support cost data. Updated defence plans and operational scenarios affecting future operations are also important inputs to in-service reviews.

SoS Considerations for an in-service review include user *capability* considerations. In particular the reviews consider any changes in the current or future operational context for use of the system (including threat, environment, usage, etc.), and whether changes impact the way the system needs to work with other systems supporting the user capability. The system may be performing as planned but changes in the user context may indicate the need for updates in the system to address new or emerging user needs. They also consider whether the non-material aspects that contribute to the capability mature and are aligned so that the capability is being fully exploited as planned. From a *technical* perspective the review considers whether any changes in the operational context of the system affect the system? From a *technical/management* perspective, if one or more recognized SoS have been established since this system was fielded which involve this system, it is important that the SoS SE organizations for these SoS are consulted to ensure the needs of the SoS are considered in the planning for the system. Further, proposed upgrades to other systems in the SoS should be factored into upgrades to this system. Finally in terms of *management and cost*, for any user requirements which involve other systems (e.g. interfaces, new or changed functionality in other systems), it is important to assess whether these other systems made changes or are planning to make changes which impact this system (or vice versa) and to assess whether these impact the ability of the SoS to support the user. These SoS considerations should then be factored into plans for upgrades to the system.

SoS technical data ideally available to support the in-service review includes results of any ongoing SoS testing/analysis which could help to identify shortfalls in user capability, an updated SoS architecture which would provide the framework for understanding how constituent systems support the SoS capability, and updates on interdependencies among systems and non-material aspects supporting capability areas which could affect the system under review.

4.0 SUMMARY AND CONCLUSIONS

Today almost all defence systems are part of one or more SoS. Despite recognition of the importance of SE for SoS, most national acquisition processes focus on systems. Unless the SoS context is considered early and throughout acquisition, significant risk to the effectiveness and successful fielding of the system.

The TTCP SoS Recommended Practices guide builds on the collective knowledge of the broader SoS community to provide a common tool to be used by program managers, systems engineers and system developers across the lifecycle to ensure SoS considerations are addressed to reduce risk in systems' ability to successfully support user capability needs once deployed.

A cross cutting issue is the need for consistent SoS supporting technical data for addressing system SoS considerations throughout the lifecycle. In many cases there is no acquisition or engineering activity at the SoS capability level to provide the SoS technical context for systems. This means that the system developer is left with the responsibility to gather the needed data to address potential SoS issues for their system, since whether or not there is an existing formal SoS engineering activity, the risks to systems of not addressing SoS consideration are real and should be addressed as early and completely as possible.

