System of Systems Reference Models

Summary Report

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1. INTRODUCTION

1.1 Scope and Content of the document

This Summary Report synthesises the main outcomes of the study performed in the frame of the ESA contract n° 21205/07/NL/HE "System of Systems Reference Models" between January 2008 and April 2009.

The objectives of this document are to provide a concise overview of the different tasks that have been performed in the frame of this study. In particular, it aims at:

- Presenting the analysis and selection process leading to the choice of the reference SoS.
- Presenting guidelines for architecting SoS.
- Presenting the adaptations made to the CDF to host a SoS study in terms of process
- Presenting the main lessons learned and recommendations issued during the demonstration.

1.2 Study context and objectives

The study reflects the current move of the space missions from asset-design to service-design, with the space component being only a part of the whole system. This is particularly obvious when we consider the programs currently under development, like GMES or SSA.

The European Space Agency has introduced SoS on a programmatic level to address two fundamental aspects of emerging and future space missions, namely the integration (and interoperability) of the existing space assets of Europe with each other and with external services, and the move from a product oriented system design to a service oriented design, focussing on the requirements from the end user in the different societal areas.

In this context, the main objective of the study is to provide a set of tools and methodologies to allow the Agency to correctly apprehend this new trend. Six steps are proposed to reach this objective:

- To analyse SoS Architectures in the frame of existing and future ESA missions and to deduce requirements for Modelling and Simulation to support SoS Architectures trade-offs.
- To perform a survey and assessment of existing tools and methods to communicate SoS Architecture concepts.
- To analyse in detail SoS in the space domain and selection of a Reference SoS.
- To provide the specifications for the tools and methods and specify performance parameters to be used during a SoS concurrent engineering session and provide detailed specification of the work plan needed in order to execute a concurrent engineering study.
- To prototype the reference models to support a concurrent design scenario for SoS.
- To perform a proof of concept demonstration of the concurrent design approach for a SoS using the ESA CDF environment and the selected reference SoS scenario

1.3 Presentation of the study team

The synthesis presented in this document is based on contributions provided to Thales Alenia Space by all the members of the study team (Thales Communication France, J-CDS).

JAQAR Concurrent Design Services

The respective roles of the study team partners were:

- Thales Alenia Space (France and Italy)
  - Prime contractor
  - Experience of space systems, complex system engineering and ESA missions
- Thales Communications France (France)
  - Knowledge of methodology, design and validation of SoS architecture
- J-CDS (Netherlands)
  - Knowledge of Concurrent Engineering and in particular the ESA CD process and tools

1.4 Overview of study key outcomes

The objectives were to define reusable, methodological and domain assets, allowing to build SoS, and to customise, where necessary, existing methods and tools, in order to capture essential features of SoS able to deliver new services to support future space missions, and non space missions where space assets provide value. After a survey of the existing architecture frameworks, methods, languages and tools, and a study of the different candidate SoS, the main tasks of the study were:

- To select the reference SoS: the **Space Situational Awareness**
- To model this SoS to allow the development of the different views
- To customize the different tools
- To perform a demonstration in the frame of the ESA CDF, to present the new methodology and process, and to see what adaptations are needed.

Lessons learned from the SoS study can be synthesized in seven major points:

1. Vision and roadmap: the SoS architecture build upon a vision and a roadmap to deliver value added services, using assets controlled by different organizations.
2. Organization for SoS Architecting: an architecture board shall group together the main sponsors of the SoS architecture, the SoS Architect, Service operators, System Design authorities, and Cost, Risk and programmatics Authorities as the 'watch-keepers' of a feasible target architecture.
3. Process and timeframe: starting from a baseline architecture ('as-is'), the process helps to discover key requirements from different, essential, perspectives: Strategy, operation, System, Technology, Programmatic.
4. Method & tools to evaluate and compare alternatives of architecture: some COTS provides a basis for multi-criteria evaluation.
5. TOGAF phases A-F map well on the scope of CD activities (applicability in TOGAF phases G and H to be investigated) and tasks map well too. However, session sequence is an issue, having more time in between sessions is advisable. ESA SoS feasibility negotiation and preparation phases last much longer than now in CF.
6. Design of SoS is at completely different level than design of system. A new mindset and different approach to problems is required.
7. A new role has been identified, i.e. the Watchkeeper. This role is actually performed by the Risk, Programmatics, Cost and Simulation domain. As SoS often works with existing assets the Watchkeepers are involved to critically assess the inputs provided by the asset experts.

2. SYSTEM OF SYSTEM ANALYSIS AND SELECTION

2.1 Analysis and selection of a reference System of Systems

The first step consists in the analysis of candidate SoS including space components - GEOSS, GMES, Navigation, Human Exploration, SSA, and civil security and telecom - through the following axis:

- What is the general architecture of the SoS?
  - components constituting the SoS, overall environment with applying constraints, users and stakeholders, governance, planning, operational concept
- What are the SoS intended capabilities and services?
- How do the different systems composing the SoS interact?
  - Interfaces between systems, towards the users, standards, interoperability requirements

Space SOS analysis shows high similarities with military SOS: this justifies the use of methodologies developed for military applications. The idea is to borrow the best practices to identify the correct interface between the present CD technical / engineering work and the SoS level.

Different criteria, with a weighting coefficient (they don't have the same importance and relevance) are used for the selection of the reference SoS:

- "Generic criteria" of a SoS : operational independence, managerial independence, evolutionary development, emergent behaviour, geographic distribution
- Maturity
- Availability of the documentation
- Identified list of participating assets
- Complexity and defined scope
- Multiple defined users/stakeholders

The proposed reference System of Systems is: **Space Situational Awareness.**

2.2 SSA Presentation

2.2.1 Introduction

The overall aim of the Space Situational Awareness (SSA) initiative is to support the European independent utilisation of and access to space for research or services, through providing timely and quality data, information, services and knowledge regarding the environment, the threats and the sustainable exploitation of the outer space surrounding our planet Earth.

The ESSAS will be a distributed system of systems, building on existing space surveillance sensors/systems while accommodating new components needed to fully satisfy the user needs. Members participating in the program will determine ways and means of their participation in SSA.

As defined by ESA, SSA is the understanding and maintained awareness of (a) the Earth orbital population, (b) the space environment, and (c) possible threats. Beyond this general definition of what is SSA, the user needs have been defined through a series of meetings with the SSA User Group gathering experts/potential users of the ESA members.

An high level architecture for the European Space Situational Awareness System (ESSAS) is presented on Figure 2-1. This architecture identifies the relationships between the ESSAS and the users, the external data sources, the sensors and the external systems. All the information exchanged between these elements through the SSA are constrained by the data policy and the governance rules.

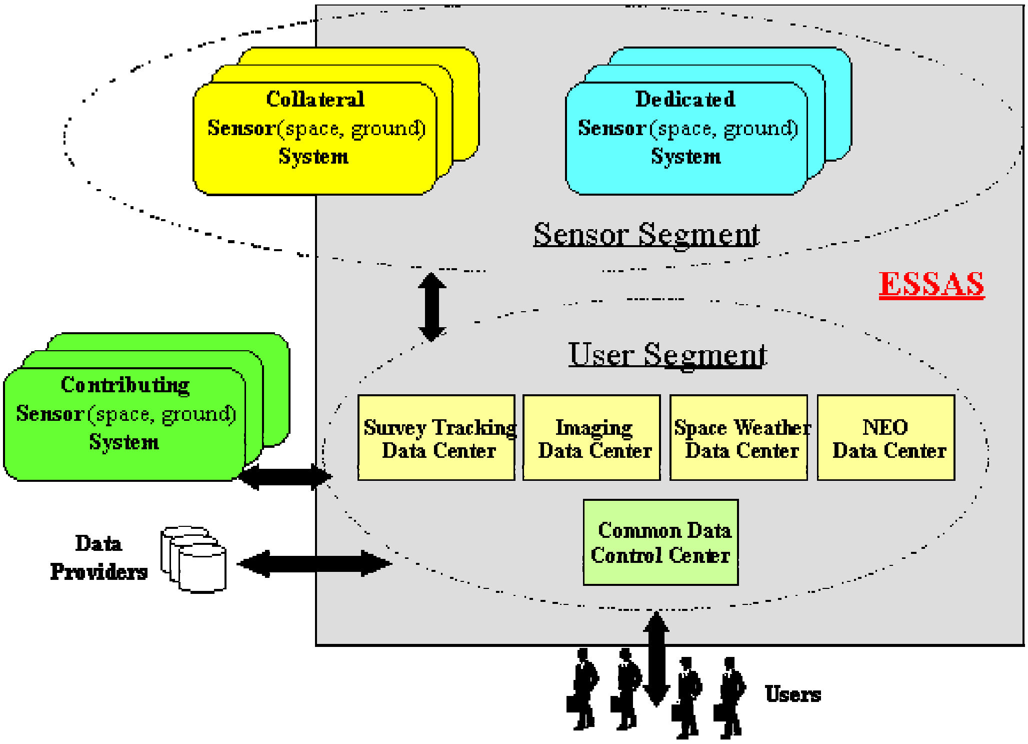


Figure 2-1 : SSA high-level architecture

2.2.2 SSA functions

SSA shall ensure the following functions:

- To acquire data, using existing European sensors/systems to be augmented as required;
- To process data into useful products;
- To exchange, disseminate, and archive shared data, metadata and products;
- To monitor performance against the defined requirements and intended benefits.

To achieve these functions, SSA will federate several heterogeneous sensors, data sources, infrastructures that are networked by an information system, as shown in Figure 2-1. It mainly consists of a Sensor and a User segment:

- **Sensors segment** with sensors that are existing or future, ground or space-based, dedicated or contributing sensors
- **User Segment**, with "Data Centres" per thematic area and per country, and a "Common Service Element" for Common & generic functions (user services, tasking, security, supervision, etc)

2.2.3 Operational constraints

SSA operation concept is ruled by a set of policies, that are critical for the existence of the program, and still to be defined

- Data dissemination policy
- User policy: management of various User profiles & privileges
- Sensor policy: management of resource and data from collaborating sensors
- Governance

Different solutions are envisaged to correctly treat those aspects. Establishment of user profiles, for example, is used to cope with some confidentiality and priority aspects. A lot of services and data will be submitted to the data policy.

2.3 Scoping

Aim of the scoping is to reduce the scope of the SSA to the part that will be used for the demonstration. Indeed, considering the SSA as a whole would imply a work load not compatible with the development of a prototype. Besides, for the purpose of understanding the methodology, it is more interesting to focus only on some points than to consider the whole System-of-Systems. It means that during the sessions, trade-offs will be performed with a limited number of systems.

The starting point is given by the user needs : the user group defined SSA as the understanding and maintained awareness of (a) the Earth orbital population, (b) the space environment, and (c) possible threats. For the purpose of the scoping, we consider here **only the points a and c**, assuming that the space environment monitoring requires separate means, while Earth orbital population monitoring and possible threats are linked.

Then the notion of temporal priority is established. Some services are required for IOC (Initial Operating Capability), some other for the BOC (Baseline Operating Capability) and some other for the EOC (Enhanced Operating Capability). If we consider **only the services that will be available at IOC**, the list of services resumes to the following ones:

- Detection and/or tracking of man-made objects
- Determination of orbit state and covariance information
- Identification of spacecraft manoeuvres
- Predict and assess the risk to humans and property on ground and in air space due to re-entries
- Detect on-orbit explosions and release events (accidental or intentional)
- Predict and/or detect on-orbit collisions (accidental or intentional)

Then the last proposed restriction consists in the **limitation to the objects in LEO**. This makes sense, because more than 86% of the tracked objects orbiting around the Earth have a perigee lower than 2000km. Besides, it is the only type of orbit for which atmospheric re-entry has a sense, and it is where collisions occur more frequently.

Based on these restrictions, the list of Sensors considered is given in the table below:

Sensor	Type	Location	Availability	TRL
GRAVES SYSTEM	Radar	France	Probable	9
TIRA-L	Radar	Germany	Probable	9
TIRA-Ku	Radar	Germany	Probable	9
UHF Radar (Step 2)	Radar	Spain	High when developed	6

A Data processing Centre, representing the user segment shall be added to constitute the list of the systems that will be considered in the study.

3. SYSTEM OF SYSTEMS ARCHITECTING

The Performance Reference Models is based on the following elements:

- **Description views** (Strategic, Programmatic, Operational, System, Technical)
  - Including Operational Services and System provisioning options
  - Strategic views define capabilities and mapping to operational services
  - Programmatic view define roadmaps operational services and system provisioning options.
- **Drivers and rating parameters**: list of drivers relevant to SOS, including programmatic and organisational constraints
- **Evaluation**: aim of evaluation is to quote alternatives of architecture. This relies on key selected criteria (Cost, Life cycle Cost, Risks, Schedule, Performance…)
  - Evaluation views
    - System Assets comparison evaluated vs. programmatic/capability increment
    - System Service provision options, evaluated vs. programmatic/capability increment
      - An Option identifies the triplet (Ops x Sys x Tech), options are distinguished by retained assets (or configurations of same asset)
    - Comparison diagrams based on Positive/Negative Criteria, criteria weights may be changed dynamically.
  - Evaluation Reports
    - Capability coverage or service coverage per feasible increment (at expected Milestones)
    - Generated from views, rating drivers, Criteria weights, and comparison views.

The following approaches are selected to articulate the SOS Performance Reference Models methodology:

- **TOGAF** provides an iterative, collaborative process to design, evaluate, and build Enterprise Architectures. The TOGAF Architecture Development Method (ADM – see Figure 3-1) allows to define SOS requirements issued from multiple architecting activities to meet the business and information technology needs of an organization. Eight phases are defined:
  - The Preliminary phase outputs architecture principles, framework definition, restatement of business principles, goals and drivers.
  - Phase A (Architecture vision) sets the scope, constraints and expectations of the architecture iteration
  - Phase B (business architecture) documents the fundamental organisation of the business
  - Phase C (system architecture) documents the fundamental structure of organisation's systems
  - Phase D (technology architecture) develops 'as is' and target technology architecture to implement.
  - Phase E (opportunities and solutions) identifies major implementation projects and build migration plan
  - Phase F (migration planning) analysis cost benefits and risks, and produces an implementation roadmap
  - Phase G Obtain signatures on architecture contract & monitor implementation

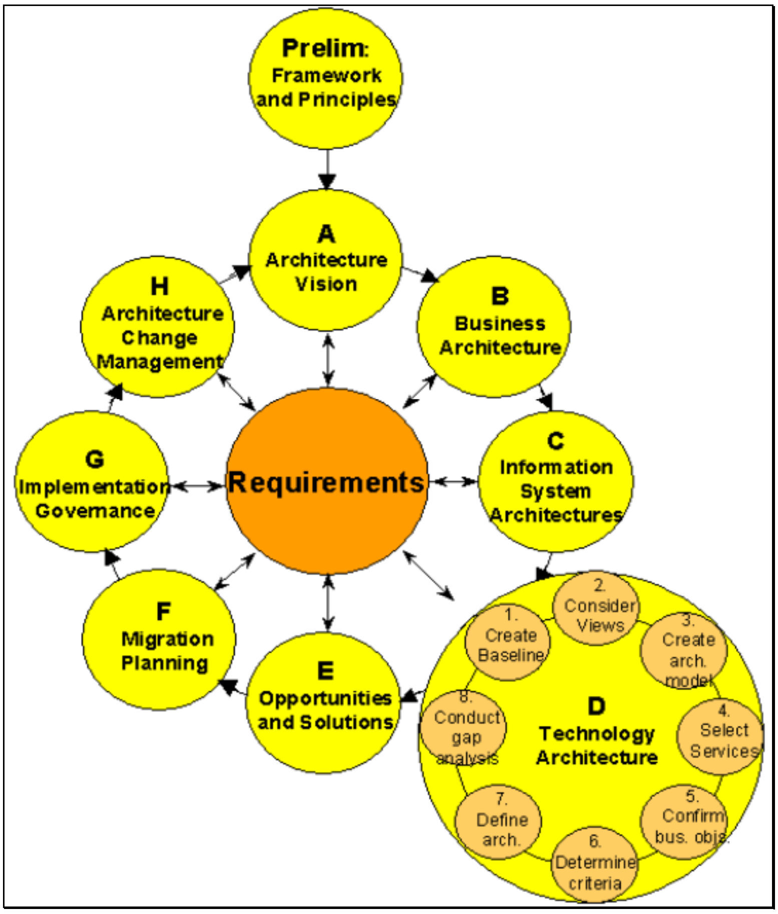


Figure 3-1. TOGAF's Architecture Development Cycle

- **NATO EAM** provides high level guidelines for developing SoS architecture description views, as shown in Figure 3-2.
  - Step 1 determines the intended use of the architecture, in order to refine initial system analysis. It *helps to discover additional key requirements or constraints that may affect the target architecture*, from many viewpoints: capability, operational, system, technical or programmatic. It also defines the analysis methods that will be used to assess architecture descriptions at each iteration of the architecting process
  - Step 2 determines the scope of architecture: geographical bounds, time-phases, functional or technical bounds, architecture resources and schedule are identified and managed so as to set the context and key assumptions and constraints, and to define the appropriate level of detail to be captured to correctly handle identified constraints.
  - Step 3 determines key requirements the architecture needs to address. Care is taken to accommodate future tailoring, extension or reuse of the architecture within predictable resource limitations. Measure of performance are defined to cope with intended use and possible future uses of the architecture.
  - Step 4 determines *which views should be built, depending on constraints* and key requirements refined on steps one through three. This gives more information must be gathered to build the required views and subviews. DODAF has refined Step 4 to distinguish two sub-processes:
    - Collection, organization and storage of architecture data
    - Analyses in support of architecture objectives

- Step 5 builds *the requisite templates (architecture description products).* For each identified architecture description template, key drivers and relevant attributes are identified and challenged in NAF v3 architecture views allowing to represent the best tradeoffs between needs constraints.

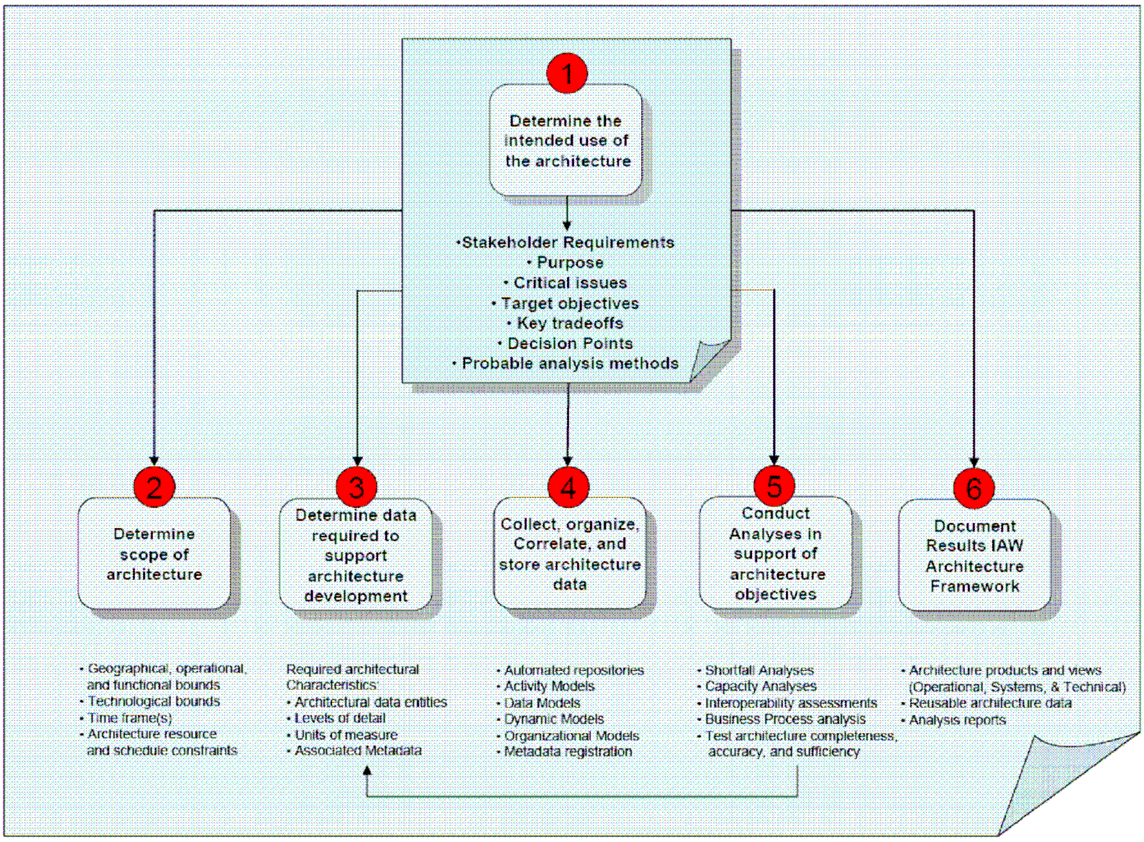


Figure 3-2 Five-Step NATO Process for Developing an Architecture)

- The **NATO architecting & engineering method (AEM)** recommends using the NAF to generate reports aimed at the users of an architecture, such as acquisition personnel and systems developers. The AEM distinguishes the "production" from the "reporting" of an architecture and provides for essentially two separate frameworks. NATO-AF is selected as it is the more complete description framework. NAF refines, and completes DODAF with Strategic, programmatic and SOA views, and it refines MODAF system views, and extend MODAF with SOA views. The two frameworks are to accommodate the needs of the two principal stakeholders of an architecture, the users and the architects.
  - Capability views document the strategic picture of how capability is evolving at short, mid and long terms,
  - Operational views document operational processes, organizations and context to support operational exchanges and requirements development. Operational services answers the question 'What information is used and provided by whom and with what quality?' Services form a layer, decoupling operational processes and activities from organizational arrangements of resources, such as people and information systems. As such, services abstract from distribution, interoperability and implementation issues in the system-layer;

- System views document system functionality and interconnectivity to support system analysis and life cycle management
- Technical views document policy, standard, guidance and constraints to specify and assure interoperability of systems provisioning the services. Standard may be public standards, enterprise standards, or domain standards. Technical Standards Forecast subview (NTV-2) is to identify emerging, obsolete and fragile standards, and to assess their impact on the architecture and its constituent elements. A forecast addressing emerging standards will give insight into the direction that the architecture project will go.

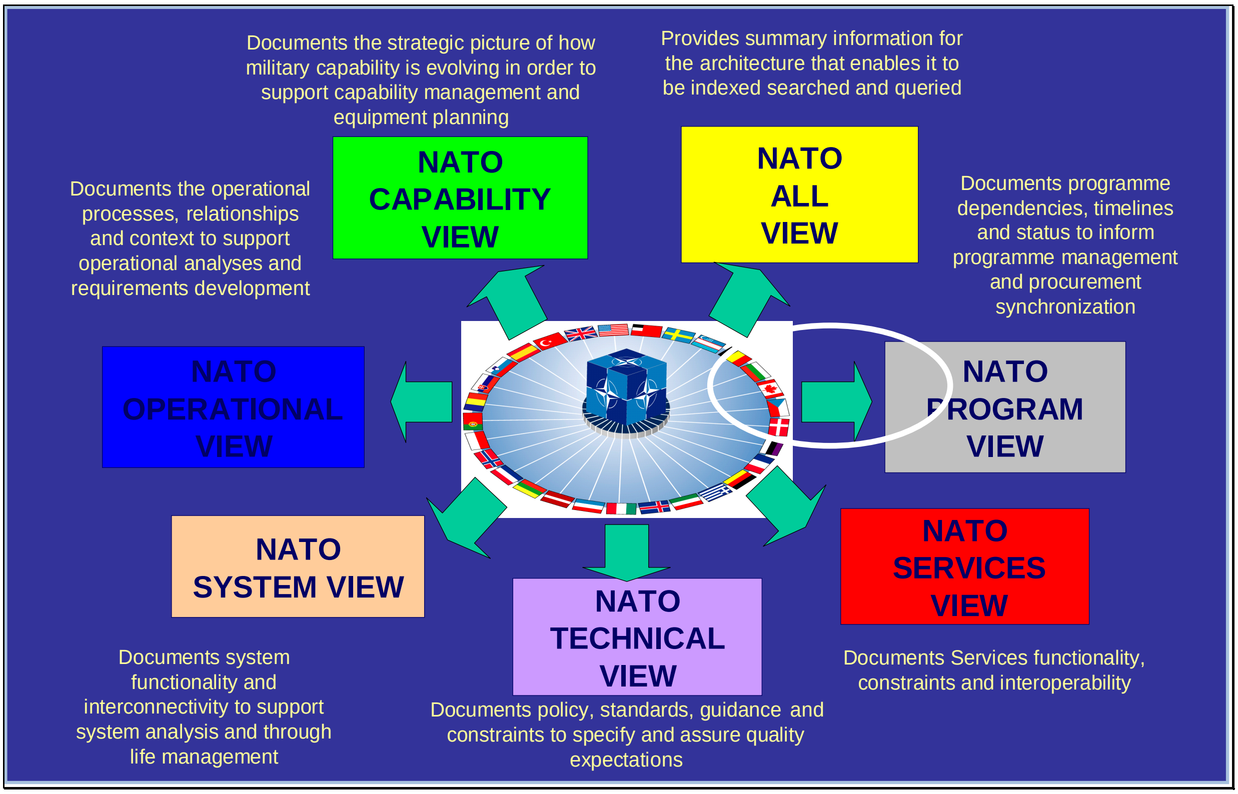


Figure 3-3. NATO Architecture Framework Views (NAF V-3)

The **AoA analysis guide** for performing analysis studies is recommended for determination of possible SoS architecture alternatives and elimination of non-viable ones. An analysis of alternative (AoA, see Figure 3-4) is an analytical comparison of the operational effectiveness and cost of proposed materiel solutions to shortfalls in operational capability (these capability shortfalls are also known as mission needs). AoAs document the rationale for identifying and recommending a preferred solution or solutions to the identified shortfalls. Environment changes, deficiencies, advances in technology or the obsolescence of existing systems can trigger an AoA. Additional direction during various AoA reviews may insert yet other alternatives.

Practically, the range of alternatives must be manageable. If there are too many alternatives, there will be inadequate resources to perform the analysis. If not enough alternatives are considered, the AoA may not be credible or may not identify the most promising alternative(s). Selecting too few or too many are both possibilities, but experience has shown that selecting too many is the greater danger. The goal is to consider a comprehensive set of alternatives representing all reasonable solutions.

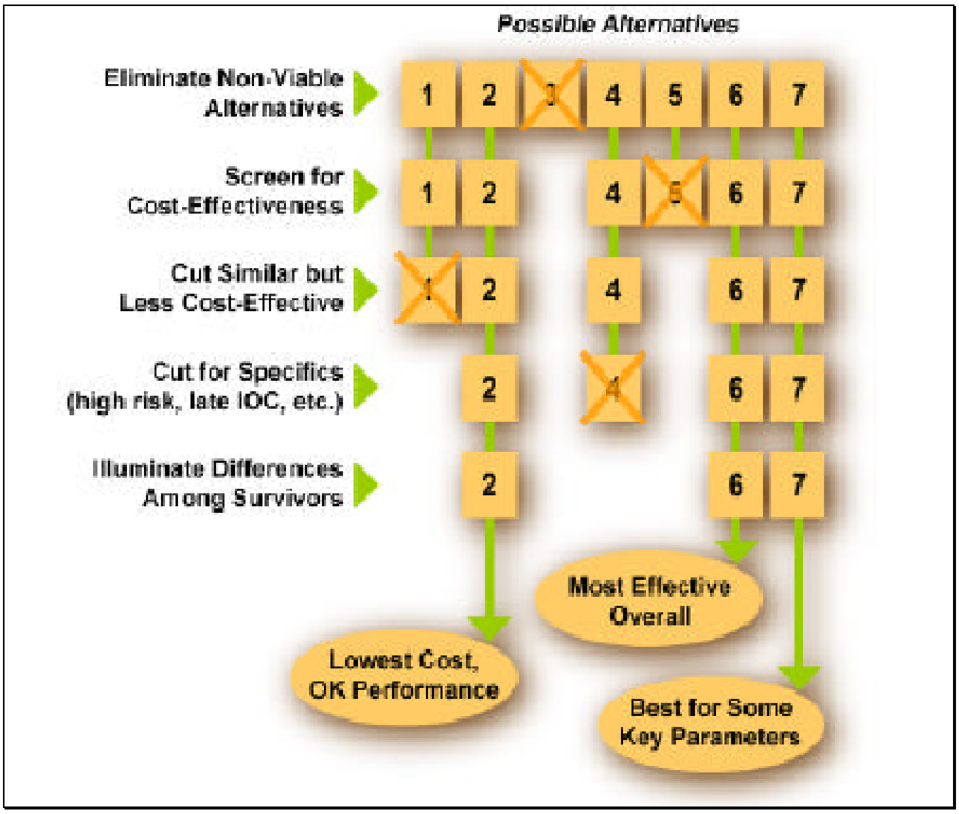


Figure 3-4. Comparison of Alternatives of Architectures

The number of alternatives can be controlled by avoiding similar but slightly different alternatives (i.e., variations on a theme) and by early elimination of alternatives for legitimate cause, which might be:

- Non-compliance with treaties or policies
- Unacceptable high cost
- Unacceptable performance
- Unacceptable risk

AoA results are usually briefed at high levels in the operational Authority and the acquisition Agency, and are used in the decision making process to support acquisition of new capabilities and systems.

4. SOS METHODOLOGY CUSTOMIZED FOR ESA PROJECTS

Considering the frame of a feasibility study, the Customisation for ESA of the SOS methodology includes the customisation of standard methods, of COTS tools, and the identification of standard Architecture description Models.
The results of the ESA Architecting process, produced during the sessions, are:

- Vision of target Architecture including current status (as-is baseline),
- Description of Alternative of Architectures (AoA) also called “Architecture Options”,
- AoA Comparison report taking into account key Enterprise Criteria,
- Gap analysis and opportunities,
- Roadmap to target (‘to be’) Architecture

The ESA SoS feasibility process is mainly an adaptation (using the TOGAF framework) of the CD process to enable SoS feasibility assessment and conceptual design. At a high level the mapping of the two methodologies is given in Table 4-1.

TOGAF	CDF-like environment
Covers complete architecture Life Cycle	Covers ESA phase 0/A Feasibility Phase, phase B reviews
Phase 0, phases A-H	Negotiation – Preparation – Sessions – Reporting
Iterative between all phases and tasks	Iterative process during sessions - spiral model
Elements of TOGAF • Outline for process • Different teams per viewpoint • Open selection of models (NAF, DoDAF…) • Open selection of tools	5 central elements of CD: • Process • Multidisciplinary Team • Integrated Design Model • Software Infrastructure • Facility

Table 4-1 Comparison of TOGAF and CD principles

And a mapping of the phases is given in Table 4-2:

CDF phase	Related TOGAF phase	Objectives
Negotiation phase	Phase A	Define SoS goals, preliminary SoS requirements and breakdown Develop statement of Architecture Work
Preparation phase	Phase A	Identify needed disciplines and team members Customise environment and tools Refine SoS goals, requirements and breakdown Develop baseline and target Architecture options
Sessions phase	Phases B-F	Refine and discuss baseline and target Architecture options Session dedicated to TOGAF phases B, C, D and E&F
Reporting phase	Use of TOGAF reporting tasks	Gather inputs from architecture teams Create report

Table 4-2 Mapping of TOGAF and CD phases

Some adaptations have been made to adapt the CD process to the new methodology:

- Adaptation of CD activity workplan and sessions workplan to SoS needs, the used sessions workplan is depicted in Table 4-3
- Addition of new **team** members: Architect, Architect assistant, Watchkeepers (Cost, Risk, Programmatics, Simulation)

- CDF Integrated Design Model **WorkBooks**: addition of Performance Evaluation Matrices at system and technology level, addition of new parameters to characterise assets in SoS
- New **tools** have been added, leading to an update of the information flow.
- IDM and Tools have been integrated and interfaced to provide the software architecture in line with the scope of the demonstration, as depicted in Figure 4-1

Session	TOGAF Phase	NAF view	NAF Products
KO Session	Phase A Architecture Vision	Architecture Vision, possibly Operational View	Architecture Vision; NCV-1 and NOV-2; other NOV-4, NSOV-3, NSOV-4
Session i to i +x - Phase B sessions	Phase B Business Architecture	Operational Views	NCV-1 and NOV-2; other NOV-4, NSOV-3, NSOV-4
Session j to j +x - Phase C sessions	Phase C Systems Architecture	System Views	NSV-1, NSV-8, NPV-2
Session k to k +x - Phase D sessions	Phase D Technology Architecture	Technical Views	NTV-1, NTV-2, NTV-3
Session l to l +x - Phase E & F sessions	Phase E Opportunities and Solutions Phase F Migration Planning	SoS Configuration and roadmap	Combination of products
IFP Session	Phase E Opportunities and Solutions Phase F Migration Planning	SoS Configuration and roadmap	Combination of products, presentation of results

Table 4-3 Demonstration session workplan

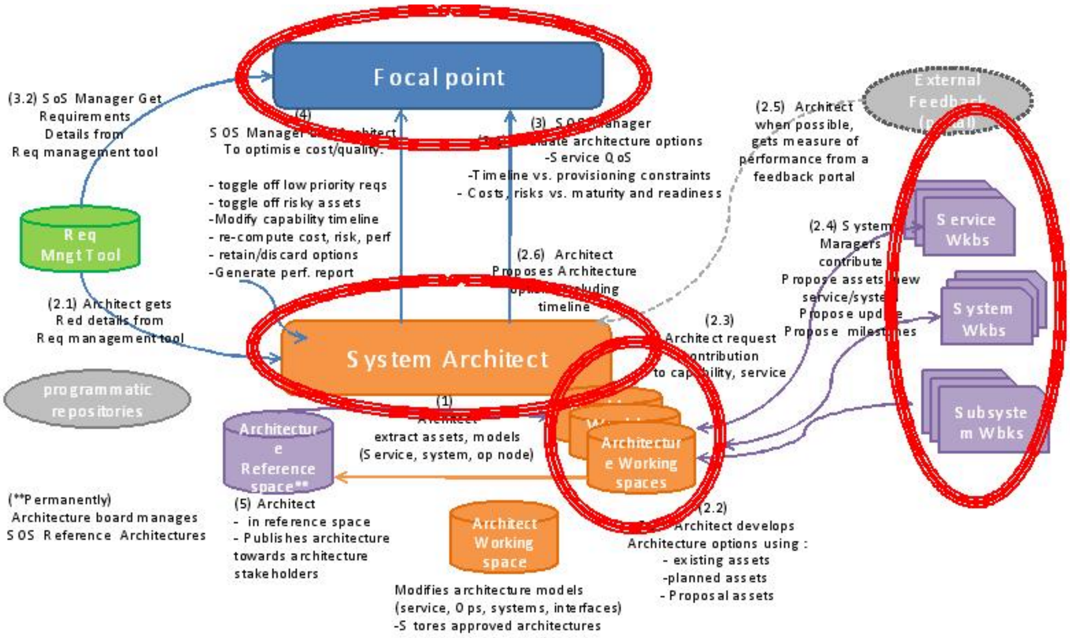


Figure 4-1 Circled in red, the building blocks integrated in the demonstration software architecture

5. DEMONSTRATION

The objective of the demonstration is to confront the new methodology and tools to the CDF environment. From a CDF point of view, the main objectives are to demonstrate the CDF capabilities for SoS, to develop / improve the integrated architecture model, by using the SSA-SoS as an example.

8 sessions have been scheduled between the 13th of January and the 19th of March, following the planning given in Table 5-1.

Session #	TOGAF phase	Objectives
Session 1 KO	Phase A - Architecture Vision Phase B - Operational Architecture	Introduction of Study Present and fix Operational View
Session 2-4	Phase C - System Architecture	Develop and discuss System View Options corresponding to OV Option Evaluate performance parameters and Service Provisioning View for System View Options
Session 5-6	Phase D - Technical Architecture	Develop and discuss Technical Views corresponding to OV and SV Options Evaluate performance parameters and Service Provisioning View for Technical Views
Session 7	Phase E - Opportunities & Solutions Phase F - Migration Planning	Perform trade-off analyses for Architecture Views Discuss and evaluate SoS configurations Perform gap analysis for SoS Configurations Discuss and adjust migration plans for SoS Configurations
Session 8 Internal Final Presentation	Recap	Presentation and final review of SSA Architecture Freeze resulting SSA Architecture Prepare for the reporting phase

Table 5-1 Planning of CDF sessions

According to the SSA vision (Figure 5-2), two strategic views were built following the NAF template: capability taxonomy and capability phasing (see Figure 5-1).

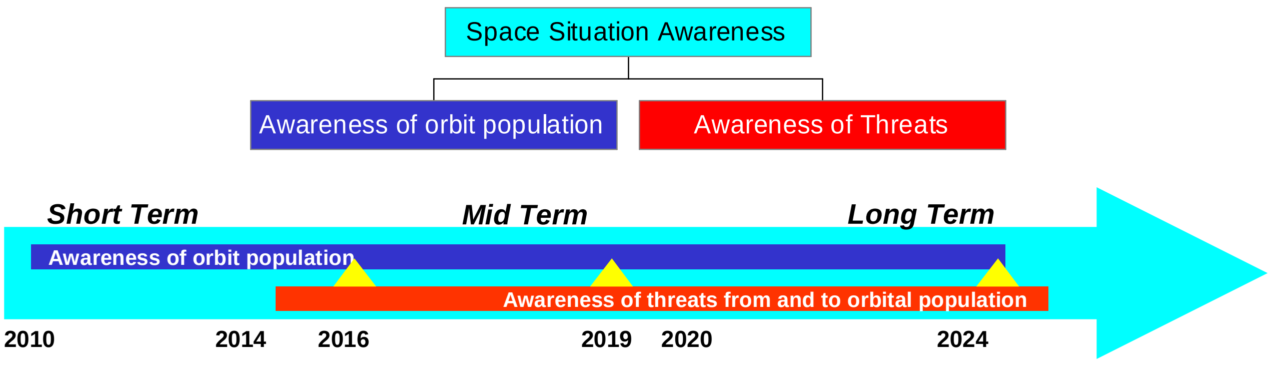


Figure 5-1. Examples of SSA strategic Views: Capability Taxonomy (above) and Capability Phasing (below)

The SSA VISION

The Space Situation Awareness will be a highly effective, near real-time and reliable solution that will underpin the ability of governments, space operators, insurance companies and defense agencies to get a better understanding and a maintained awareness of the population of space objects, of the space environment and of existing threats and risks. By providing to the users verifiable, dependable, accurate and timely information, it will serve the implementation of the strategic missions of the European Space Policy based on the peaceful uses of outer space by all states.

A number of SSA capability goals have been drawn from the vision:

Capability Goal 1	Support safe and secured operation of space assets and related services
Capability Goal 2	Support risk management (on orbit and during re-entry) and liability assessment
Capability Goal 3	Assess the status and basic characteristics of space objects (both human-made and natural)
Capability Goal 4	Detect non-compliance with applicable international treaties and recommendations
Capability Goal 5	Enable the allocation of responsibility for space objects (as launching state), and support confidence building measures (identification of owner and/or operator)

Figure 5-2. Examples of SSA Strategic view: Capability Vision

During phase B, the demonstration team agreed on the operational architecture of the SSA as proposed by the architect (the proposal was built during preliminary phase of the ADM), which depicts major operational nodes willing to interoperate in order to deliver SSA services. This corresponds to the operational view NOV-1, see Figure 5-3.

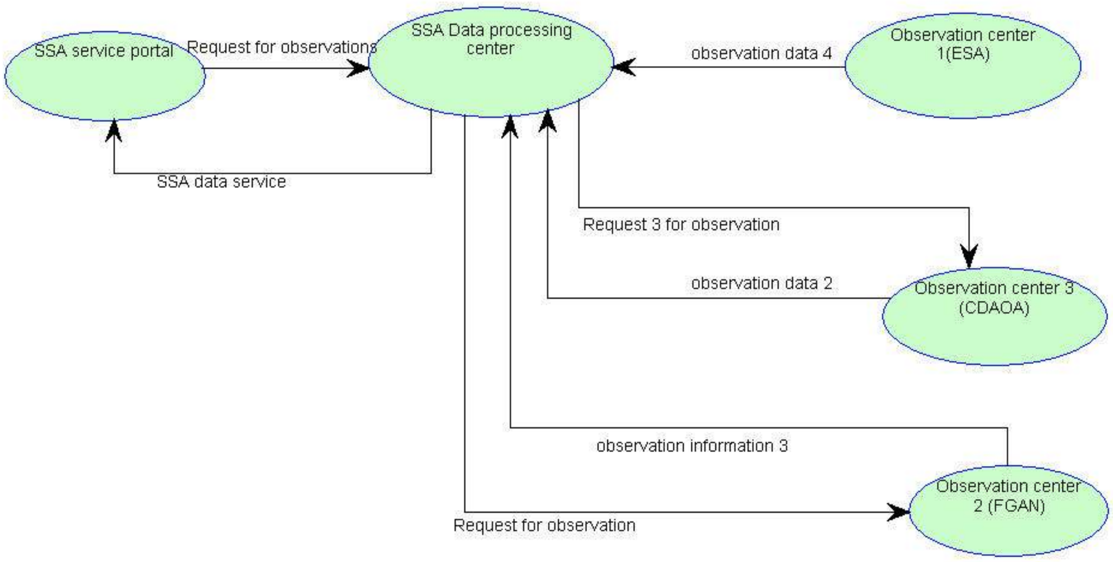


Figure 5-3 Operational View NOV-2

SSA services map to expected capabilities as depicted in the following strategic view (see Figure 5-4)

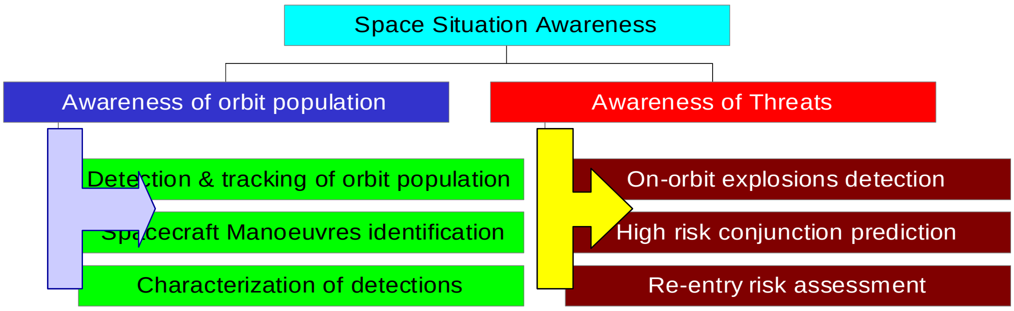


Figure 5-4. Examples of SSA strategic Views: Capability to Service Mapping

The operational view is derived into System views, see Figure 5-5. They show what system is resident in each system node, and how they collaborate to support the operational domain's information and information exchange needs defined in the operational view.

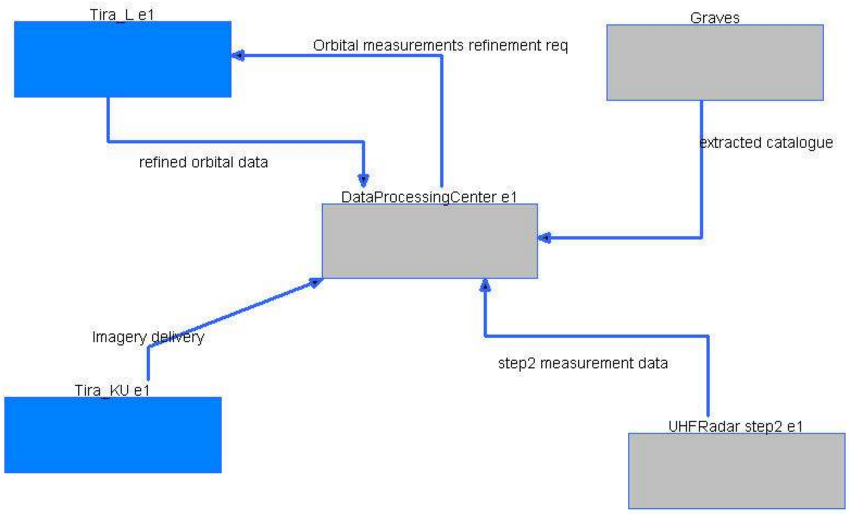


Figure 5-5 System View NSV-1 for Alternative 1

To provision identified key services, three system alternatives have been developed during phase C of ToGAF sessions. This shows that the SSA Operational architecture may be supported by a couple of (existing, to be developed, to be adapted) systems interacting through key interfaces. This provided a typical example of alternatives of architecture (AoA) an SoS, to be analysed and compared w.r.t. capability objectives and phasing constraints. SSA AoA considered hence three alternatives:

- Alternative 1 is the initial baseline, the considered assets are the Data Processing Centre, TIRA-L, TIRA-Ku, Graves and the new UHF Radar Step 2. Total adaptation costs and risk estimates are important, and the maturity of the envisaged systems is not satisfactory.
- Alternative 2 uses the UHF radar Step 1 instead of Step 2. The considered assets are then the Data Processing Centre, TIRA-L, TIRA-Ku, Graves and the new UHF Radar Step 1. This alternative improves the technical readiness of the architecture (current TRL), However, cost and risk parameters remain too high to be accepted by the customer.
- Alternative 3 removes Graves. The considered assets are the Data Processing Centre, TIRA-L, TIRA-Ku and the new UHF Radar Step 1. This alternative reduces the overall cost of the architecture, and the risk related to the availability of systems provisioning SSA services. It also reduces the overall performance.

Key issues were then refined during technical architecture session, regarding the technical standards and forecast allowing selected systems to interoperate smoothly in the target SoS configurations (network protocols, security protocols, information exchange data policies). Short term, mid term and long term standards to which selected system should adapt were identified in technical standard profile, and standard forecast views. These views impacted the time-to-capability milestones of provisioned services. The scoping of the study did not include to experiment nor to integrate some candidate systems via a prototype technical infrastructure for interoperability and security, as a proof of maturity of the proposed architecture. Deliverable DI3 describes examples of such multinational demonstration of interoperability.
For each service and each option, a Service Provision View is then produced. It serves as a basis for the evaluation of the different architectures.

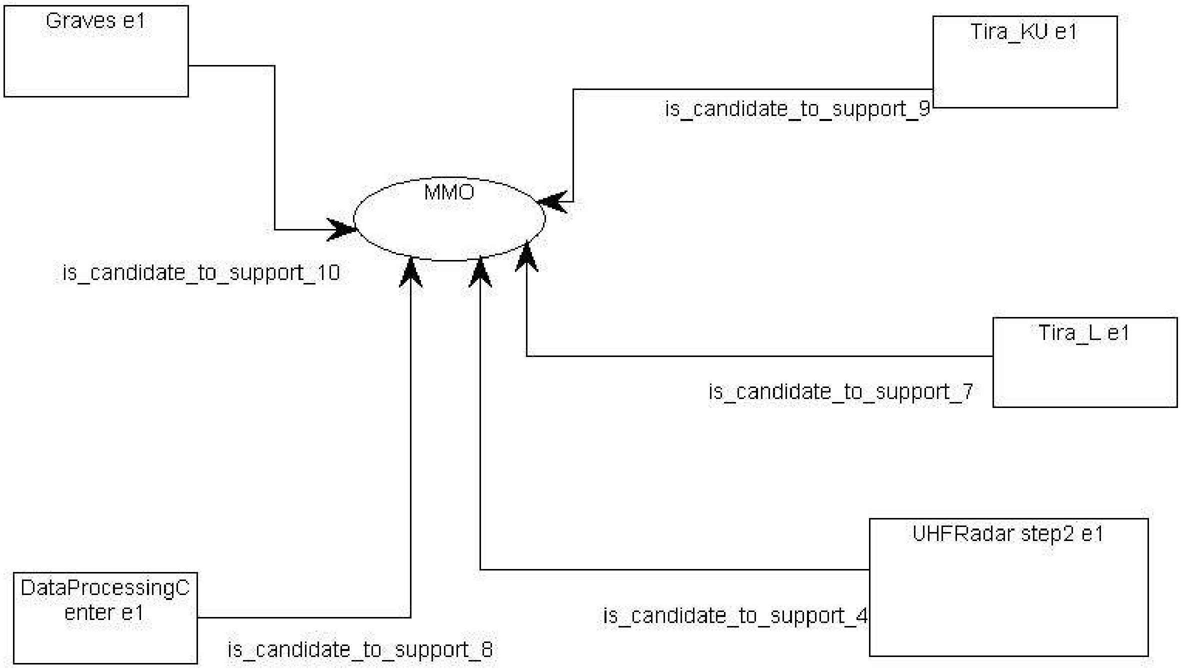
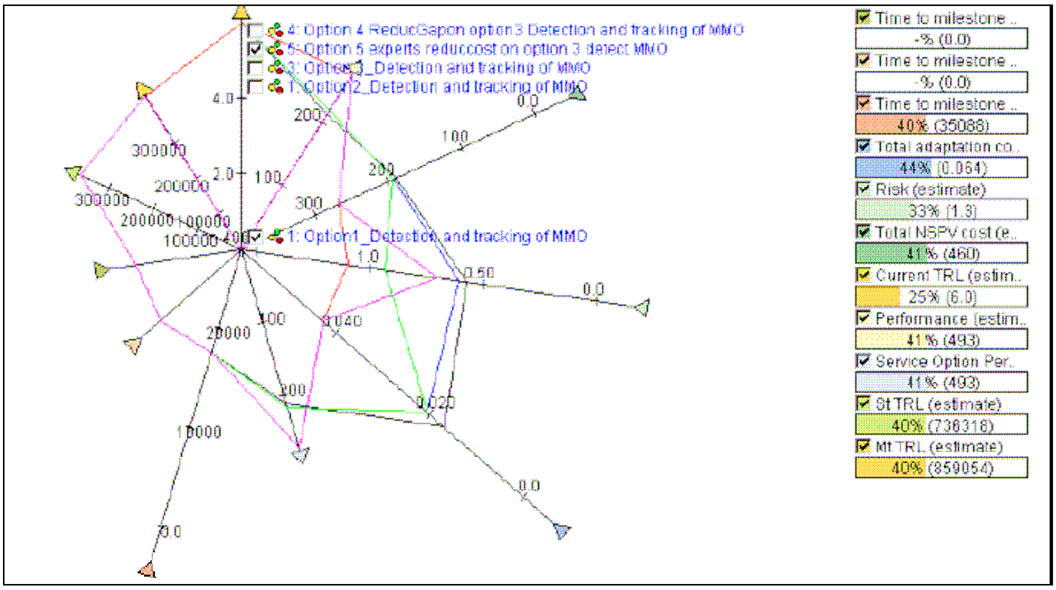


Figure 5-6 Service Provision View (NSV12) for Alternative 1 and service Detection and Tracking

Based on the ratings and information provided by the system experts and completed by the watchkeepers, evaluation of the architecture alternatives is performed at (operational) service, system and technical level, see Figure 5-7. Different criteria, whose weight can be modified according to the customer request, are used for this evaluation: Time to capability milestones, Risks, Total cost, and Performances. They are computed using business rules defining the contribution of each rating to those criteria and to the score of the service provision option.



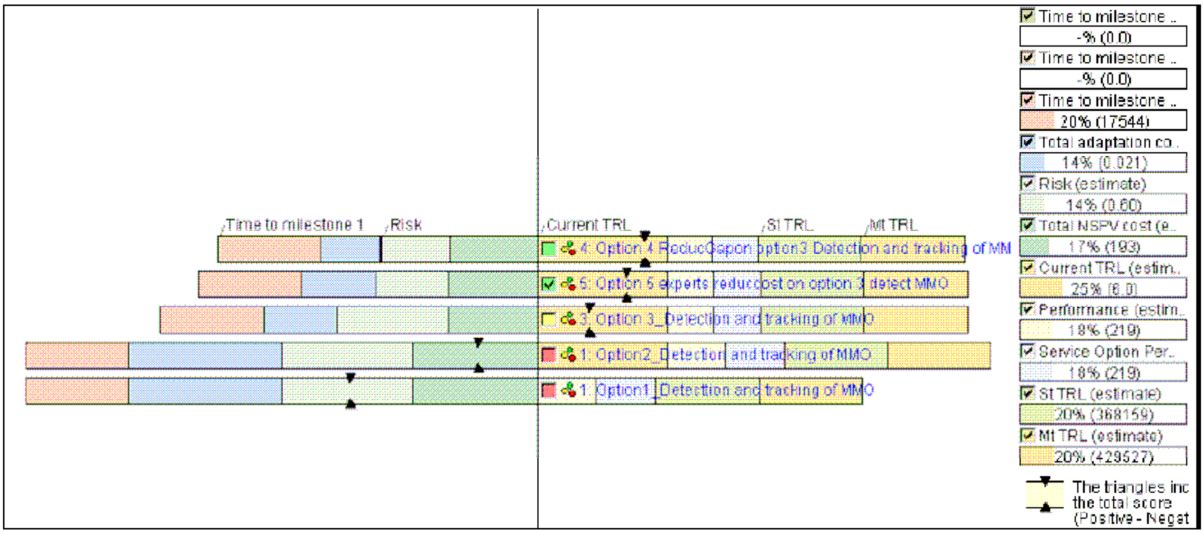


Figure 5-7 Evaluation of architectures

Results of evaluation are provided in radar (above) or bar-chart (below) form.

The evaluation allows to see the contribution of each criteria and helps to the selection of the best architecture. It is a dynamical process, it is possible to change the trade criteria and to see directly the impact.

Other alternatives have been created during the Gap Analysis session, aiming at decreasing the risks (alternative 4) or the costs (alternative 5), with obviously also an impact on the performance. Interaction process between the team members, and in particular the central role of the watchkeepers, was put in the foreground.

On the bar-chart representation, the criteria that shall be minimised are represented on the left part, the one to be maximised on the right part. The overall score, given as the difference between right and left scores, is plotted by the black triangles.

Radar representation allows to compare in a quick glance the contributions of each criteria. Relative weight of each criteria is given by the size of the related axis.

6. LESSONS LEARNED AND RECOMMENDATIONS

It appeared during the sessions that Concurrent Engineering principles are applied in normal SoS Architecting activities. An important lesson learned however was that Concurrent Design principles could enrich the normal SoS CE process, from different aspects, a) reduce the workload of the architect by the introduction of a team leader and so making a clear split between architecting and process and covering both completely, b) reduce the centralised and mono-directional data exchange and make it omni-directional, c) enhance the interaction between the stakeholders through the input and output principles of CD.

Lessons learned regard mainly the appropriateness of CD process with respect to the SoS methodology presented above. To summarize, we can say that both processes are compatible, and that SoS process requires the CE/CD process to be applied at a higher level.
Some important points may however be mentioned :

New team members have to be added. New roles are created (Architect, watchkeepers), the notion of Architecture board is introduced. System engineering is not the sole aspect, and other disciplines are requested. The level of expertise expected from the team member is not the same as for usual CD sessions, as the emphasis is not on design but on organisational, political, … aspects. A new mindset is expected from the participants.

Duration of the phases is very different, assuming that the design of a complete SoS can take 2 years, each TOGAF iteration can take 3 months. The negotiation and preparation phase is even more important than in for a normal CD study. The duration between the sessions also shall be reconsidered, with different possible options, like having only one session per week, to have enough time to gather the information, or to have sessions with different teams according to the subjects.

Vision and roadmap: the SoS architecture build upon a vision and a roadmap to deliver value added services, using assets controlled by different organizations.

Process and timeframe: starting from a baseline architecture ('as-is'), the process helps to discover key requirements from different, essential, perspectives: Strategy, operation, System, Technology, Programmatic.

Method & tools to evaluate and compare alternatives of architecture: some COTS provides a basis for multi-criteria evaluation. Adaptations have been made to enhance the data flow between the tools allowing the selection of the data (the IDM workbooks), the SoS modelling (System Architect) and the Evaluation of alternatives (Focal Point)

The scoping of the study did not include to experiment nor to integrate some candidate systems via a prototype technical infrastructure for interoperability and security, as a proof of maturity of the proposed architecture. Deliverable DI3 describes examples of such multinational demonstrations of interoperability, which delivers prototype of SoS short term configurations as baselines for rapid improvement of readiness level.

From a CDF point of view, main lessons learned can be synthesized as follows :

1. TOGAF phases A-F map well on the scope of CD activities (applicability in TOGAF phases G and H to be investigated) and tasks map well too. There are 2 main issues however:
    - Session sequence is an issue. Having more time in between sessions is advisable.
    - ESA SoS feasibility negotiation and preparation phases last much longer than now in CD process.
2. Design of SoS is at completely different level than design of system. A new mindset and different approach to problems is required.
3. New roles have been identified.

- The role of Risk, Programmatics, Cost and Simulation domain (the watchkeepers) appears to be much more important, as the Watchkeepers are involved to critically assess the inputs provided by the asset experts.
- An important group involved in SoS Architecting is the Architecture board, consisting of the customer, the Architect, and representatives of the main stakeholders. In the ESA SoS feasibility approach the Team Leader should also be part of this Architecture Board. It shall be clarified who should be part of a generic SOS Architecture Board.

4. The architecture used in the CDF SoS Case Study is the easiest to implement, but it has some drawbacks. It is not very flexible and the addition of new parameters appeared to be quite difficult. It seems a logical evolution to move towards a more integrated architecture, once the training on the methodology, process and tools is done.
5. In a normal CD process new parameters are continuously uncovered and added. Automation of the whole to be flexible with new (groups of) parameters is however not straightforward and would require additional development.
6. The tools used during the CDF SoS Case Study seemed to provide the functions and perform the tasks required, and there is no reason to doubt the applicability of the used tools for future ESA SoS Architecting activities. How far they need to be integrated/customised can be the subject of additional projects.
7. It is also recommended to train people in the use of SA and FP. The in-depth knowledge of these tools could trigger actions to better integrate the SA with the domain/asset experts, as long as the Concurrent Design process features can be added/implemented in SA.

Lessons learned from the SoS PRM study can be synthesized in five major points:

1. Vision and roadmap: the SoS architecture build upon a vision and a roadmap to deliver value added services, using assets controlled by different organizations.
2. Organization for SoS Architecting : an architecture board shall group together the main sponsors of the SoS architecture, the SoS Architect, Service operators, System Design authorities, and Cost, Risk and programmatics Authorities as the 'watch-keepers' of a feasible target architecture.
3. Process and timeframe: starting from a baseline architecture ('as-is'), the process helps to discover key requirements from different, essential, perspectives: Strategy, operation, System, Technology, Programmatic. This requires to:
   - Develop, exploit and maintain associated repositories
   - Include feedbacks from operations (namely on networking, interoperability and security issues), and inputs from specific simulations concerning domain specific performance attributes.
   - Execute architecting loops in a timeframe consistent with key issues to solve at each alternative of architecture.
4. Method & tools to evaluate and compare alternatives of architecture: some COTS provides a basis for multi-criteria evaluation. They require customizations of display and comparison modules. A reusable template was issued.
5. Method and tools to govern the implementation of the selected alternative of architecture, based on the architecture contract issued as the major conclusion of the feasibility study. The governance process relies on the programmatics views, where critical paths to the target SoS are secured by formal checkpoints.

7. CONCLUSIONS

The objective of the Performance Reference Model was to characterize the performances of the selected SoS from different point of views:

- Operational performances provided by the services
- Performance of the system architecture developed for the services
- Performance of the technical architecture implied behind the system architecture

This was made possible with the chosen methodology (TOGAF) and framework (NAF), associated to the selected tools (System Architect and Focal Point) that allowed the modelling of a first capacity of SSA in a limited timeframe despite the limitations linked to the software problems.

The CDF SoS demonstration was able to show that the SoS methodology can be applied in the framework of the ESA CDF providing that some enhancements are made. It also showed that ESA CD approach can provide an added value to the SoS Architecting way of working as it is done currently. Although some adaptation is needed both on process, infrastructure and competences, with the demonstration using the CDF infrastructure, ESA has establish a starting point for their involvement and competence for SoS Architecting.

Recommendations for enhancements have been made, the most important ones are: change mindset, training and attract right competences.

Architecting SoS requires an organisation involving all SoS sponsors, Architects, design authorities, experts (technical, Cost, Risk, Programmatics) through an Architecture contract drawing a secured roadmap from baseline to target architectures.

The TOGAF architecting framework provides guidelines to build such contract, putting multi-perspective, key requirements at the heart of the architecting process. Military frameworks (NAF, MODAF) provides meta-models and model elements to capture essential structure and dynamics of SoS elements. Modelling and evaluation tools exist as COTS, their customisation allows the SoS Enterprise to rapidly concentrate on the feasibility of SoS vision via incremental integrations of SoS configurations, to optimise assets reuse according to their proper life cycle, while minimising costs and risks of adaptations to reach the need readiness level.

System of Systems is new to ESA but also growing in importance. As they address different levels compared to present studies (engineering vs. programmatic), there is a need to:

- Apprehend the associated new methodology and tools.
- Adapt the current practices and processes.
- Train architect and architecting teams.
- Look at the whole TOGAF process, in particular, the last phase which governs architecture implementation based on synchronisation of individual system adaptation / implementation projects with studies and prototyping projects enabling the increase of technical readiness levels, this to ensure interoperability and integration of each candidate component system in the target SoS configuration.

Main objectives of the study have been achieved. SoS is new to ESA, but new tools and methodologies have been provided to help understanding this new trend of growing importance. However, an adaptation to the new processes is required. There is no doubt that the exercise could be enlarged to show the benefit of a complete modelling.

END OF DOCUMENT