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Subject: Challenges on Systems of Systems, an industry point of view

Purpose

Concept of system of systems (SoS) is now known since more than ten years, but currently we have only high-level descriptions of what is and how we can work with.
The aim of this paper is listing main challenges from an industry viewpoint on SoS regarding systems engineering and operation.
For people already knowing what SoS are, paper reading can directly start with section titled "identified challenges". In this section each topic can be read independently and in any order. For this reason few sentences are duplicated to allow understanding.

Some definitions and references

Definitions

Many definitions exist now for SoS. The most known and agreed is coming form the US-DoD:

> ***SoS*** *is defined as* ***a set of arrangement of systems*** *that results when* ***independent*** *and useful systems are integrated into a larger system that delivers unique* ***capabilities*** *(Defense Acquisition Guide Book ch.4).*

This definition relies on "system" and "capability" concepts that are known from longer time even if they are still no completely agreed definitions. INCOSE and US-DoD can be taken as baseline at least to understand SoS:

> ***A system*** *is an integrated set of elements, subsystems, or assemblies that accomplish a defined* ***objective****. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements. (INCOSE SE Handbook, v3.2, 2010)*

> ***A capability*** *is the* ***ability to achieve a desired Effect*** *under specified standards and conditions through combinations of ways and means to perform a set of tasks (CJCSM 3170.01B, May 11, 2005).*

Pragmatically aim of SoS building is to make several systems working together and to get synergy towards a common objective. Implicit wish in the construction and operation of SoS is having individual systems fulfilling their own objectives and contributing to the common SoS objectives. As long these two purposes are independent this implies constraints for systems selection, their management and operation. Regarding that SoS criteria have been defined by M. Maier[1] by end of the 90's:

1. Operational independence of the component systems
2. Managerial independence of the component systems
3. Evolutionary development
4. Emergent behaviour
5. Geographic distribution

Rapidly it was stated that these criteria are never fully satisfied by definition. As examples:

- Geographical distribution is introduced for segregation of resources to satisfy the two first criteria; but interoperability implies sharing of communication means, protocols, semantic and knowledge.
- To guaranty SoS objectives the emergent behaviour (or synergy) must be stabilised with rules towards individual systems in terms of management, operation and interoperability.

Regarding the compromises to be made in SoS engineering and operation academic researches have been done. As example, John Boardman & Brian Sauser[2] explaining balancing to be done between:

- Autonomy (independence) and Belonging to SoS
- Geographical distribution and Connectivity
- Diversity & Emergence and SoS objectives

Systems Engineering

From the systems engineering point of view the main reference is currently the U.S. DoD systems engineering guide for SoS[3]. Many other references can also be considered:

- MITRE[4]
- Barry Boehm USC - University of Southern California[5]
- D. Luzeaux – French Ministry of Defence[6]
- UK chapter of INCOSE[7]
- French Chapter of INCOSE[8]
- Etc.

But all these are far from providing a methodology and processes directly usable to systems engineer.

Identified challenges

Change #1: Loose coupling within SoS

Interaction constituent system within a SoS has to comply as far as possible Maier's criteria [1. Operational independence of constituent system; 2. Their managerial independence; 5. Their geographical distribution (segregation of their resources)]. This implies loose coupling to be studied for:

- Physical, procedural and operational interoperability
- Semantic (knowledge) sharing with respect of autonomy of each constituent system
- Federating, scheduling and managing operations of the constituent system to guaranty SoS behaviour fulfilling the SoS objectives.
  Remarks:
  - Federation of constituent systems includes here policies to guaranty that the constituent systems are

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[1] Maier, M.W., "Architecting Principles for System of Systems," Systems Engineering, Vol. 1, No. 4, 1998, pp. 267-284.
[2] John Boardman & Brian Sauser "*System of Systems* – the meaning of ***of***"
[3] The Department of Defense systems engineering guide for Systems of systems, version 1.0, August 2008
[4] MITRE System Engineering Guide, http://www.mitre.org/work/systems_engineering/guide/
[5] Barry Boehm, USC-CSSE, The incremental commitment model, GSAW 2009
[6] Systems of Systems, LUZEAUX Dominique, RUAULT Jean-René, ISTE Wiley edition, 2010
Simulation and modeling of systems of systems, CANTOT Pascal, LUZEAUX Dominique, ISTE Wiley edition, 2011
[7] Using Relational Model Transformations to Reduce, Complexity in SoS Requirements Traceability: Preliminary Investigation, Charles Dickerson and Ricardo Valerdi, 2011
Sillitto, H. 'Design Principles for Ultra-Large Scale (ULS) Systems'. Proc. 20th INCOSE International Symposium, Chicago, July 2010.
[8] Coupling component systems towards systems of systems, by Autran, Auzelle, Cattan, Garnier, Luzeaux, Mayer, Peyrichon & Ruault, AFIS, 2008

contributing the SoS behaviour in a coherent manner.
  - Scheduling can be declined as orchestration or choreography of constituent system operational activities.
  - Management of operation covers configuration, monitoring, supervision and reconfiguration. This management can be centralised or not.
- Exchange infrastructure allowing the best geographical distribution, independence and light-connectivity of the constituent systems.

Challenge #2: Paradigms for interaction within SoS

Known paradigms for interaction are currently exchanges of services, products (including data), events and streams. Clarification of these paradigms is needed to guaranty as far as possible the Maier's criteria, in particular [1. Operational independence of constituent system; 2. Their managerial independence; 4. Emergence].
These paradigms have generally to be mixed in the architecture to deal with complete features. As examples:
- Service exchanging data
- Product exchange to sustain a service
- Energy steaming trigged by events
- Etc.

In particular exchange of services between constituent systems with respect of the Maier's criteria implies to significantly improve definition on:
- Service level Agreement (contract based on service exchange), Service level specification, service level management as extension of current standards like ITIL[9] and eTOM[10].
- Service Engineering: In this domain currently standards are only covering the software development and architecture based on web technologies and do not address engineering of services at system and operational level.
  Note: This statement has been done by French Chapter of INCOSE with explanation on breakthrough on business models, life-cycles and engineering methods[11].

Challenge #3: SoS behaviour

Mastering SoS behaviour is the main difficulty due to the fact requirements are both at constituent system and SoS levels with the necessity to respect Maier's criteria [1. Operational independence of constituent system; 2. Their managerial independence; 4. Emergence]. I.e. Policies have to be studied to guaranty compatibility of the both levels with both autonomy of the constituent systems and coherency of the SoS, according to their different natures: virtual, collaborative, acknowledged and directed[12].
Several work areas are necessary to master SoS behaviour:
- Scheduling paradigms: priority-based, on-demand, periodic, earliest deadline first, etc.
- Scheduling architectural patterns: Orchestration and choreography, at least.
- Graphical notation: OMG/MARTE is [only] a good start.
- Non-functional aspects (SoS performance, security, safety and human factors). And how to decline them into functional, structural and/or organisational measures.

Challenge #4: Sos Engineering activities and life-cycle management

Current aim of the norms and standards Systems Engineering methods and processes is dealing with a single engineering solution-of-interest –generally called a system. Platforms or pieces of equipments could be understood as well; but not really for service, as explained above– These norms and standards do not address multiple systems engineering independent processes sustaining an overarching solution being a SoS.
Some tracks can be found in standards Enterprise Modelling (ISO-15704, etc) but we are far from having guidelines to work on Maier's criteria [2. Managerial independence of constituent system; 4. Emergence; 5. Geographical distribution].
The main topics with many questions in systems engineering of SoS are:
- Analysis of SoS life-cycle and engineering steps:
  - Does Life-cycle make sense for a completely open SoS architecture?
  - Is it possible to phase development strictly before operation?

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[9] Information Technology Infrastructure Library, Office of Government Commerce
[10] Tele-Management Forum, Business Process Framework, enhanced Telecom Operations Map
[11] AFIS Technical Committee (3S-AI) dedicated to Architecting and Engineering of SoS and Services. This CT is chaired by JL. Garnier (Thales).
[12] MITRE System Engineering Guide (Types of Systems of Systems), http://www.mitre.org/work/systems_engineering/guide/evolution_systems.html

  - Is the CD&E (Concept Development and experimentation) the only way to scope and issue SoS releases?
  - Does Acceptance make sense for a SoS? If no how to contract results of SoS development?
  - How to deal with emergence during the life-cycle? E.g. emergence versus verification, validation and acceptance.
- Collaborative engineering:
  - How SoS contracting can be done regarding individual constituent system contracts?
  - How risks can be shared between SoS and individual constituent systems managements?
  - How to build SoS engineering based on extended enterprise extension?

Challenge #5: Sos Engineering process

From the SoS engineering point of view with respect of Maier's criterion [2. Managerial independence of constituent system; 4. Evolutionary development] the issue is to guaranty a solution issue fulfilling the defined SoS objectives and/or capabilities, while reusing existing systems as far as possible, and requiring some new ones.
Regarding the evolution of the constituent systems, a decision process must also be found to add, replace, suppress constituent systems during the SoS life-cycle in order to always be inline with the objectives/capabilities possibly evolving also.
In this scope some ideas have been explored by French research project ISyCri[13] for crisis management. A generic process has to be imagined.

Challenge #6: SoS management, ILS and training

Considering Maier's criteria [1. Operational independence of constituent system; 2. Their managerial independence; 4. Emergence] major difficulties are foreseen in:

- SoS system management during operation (I.e. configuration, monitoring, supervision and reconfiguration): First studies [*References to selected: DSOS, E2R, E2SMS, PEA ORGRE, Modelplex, etc*] shown that SoS Management cannot be considered as only Management of Management of individual systems since SoS behaviour must take into account emerging effects varying with constituent systems independence. As exposed in a French contribution to NATO-RTO[14] a pertinent approach seems to think System management at SoS level based on reference models regularly updated to provide expected constituent systems behavioural view, expected overall SoS behaviour, and adaptive SoS management activities to be undertaken.
- Integrated logistic support (ILS): each constituent system is supposed to be operational with a supply chain and maintenance activities to sustain each system in operational conditions; but an overall approach is needed to guaranty that combination of the individual ILS performances is coherent with SoS quality of service (availability, operation accuracy, etc).
- Training on SoS: each constituent system is supposed to be engineering with development of a training process and possibly a dedicated enabling system. But there is an issue to train on the functional chains crossing the constituent systems:
  - With respect of the overall SoS policies
  - Taking into account the emerging effects and constituent systems evolution
  - Evaluating trainer and SoS effectiveness to reach operational SoS objectives and capabilities with regards of the technical SoS performance.

Challenge #7: Modelling and simulation

A strong trend is Model-based Engineering starting with formalised stakeholder viewpoints (See ISO-42010) and using model-based processes to go through the work (MBSE, MDE, MDA, etc)[15]. Evaluation of each modelling step is essential to make "early validation" or model assessment against various engineering criteria (cost, performance, schedule, completeness, etc). Model execution within simulation environment must be encouraged to

- Automate the evaluation process with replay and run-time monitoring features.
- Make evaluation with humans, and virtual, hybrid and/or real environment in the loop

Modelling and simulation is consequently a strong base today to evaluate SoS regarding Maier's criteria [1.

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[13] SyCri (Interoperability of Systems in Crisis situation), http://research.petalslink.org/display/isycri/ISyCri+Overview
[14] A Model-based Architecture for Tactical Systems of Systems Management, NATO-RTO/IST-087, Dumont, Farcet, Slimani, Garnier, Ludwig, Israel, 2009
[15] Model-oriented Systems Engineering Science: A Unifying Framework for Traditional and Complex Systems, Duane W. Hybertson, MITRE, McLean, Virginia, USA , 2009

Operational independence of constituent system; 3. Emergence; 4. Evolutionary development; 5. Their geographical distribution (segregation of their resources)].

For SoS, many different organisations (See ESA CDF[16], UK Networks[17], NATO DNBL[18], etc) are using modelling and simulation with a collaborative approach to insure a common vision of the stakeholders and feasibility of the project.
With this model-orientation approach models are seen:

- As commitment between stakeholders (Views within Architecture Frameworks[19])
- As references during Engineering (Model-Based System Engineering)
- As references during operation for the system management (configuration, monitoring, supervision, reconfiguration)

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[16] Concurrent Design Facility : http://www.esa.int/esaMI/CDF/
[17] Niteworks: http://www.niteworks.net/partnership/mod/
[18] Distributed Networked Battle Labs: https://dnbl.nc3a.nato.int
[19] DoDAF, NAF, MODAF, TRAK, TOGAF, PEAF, etc.