System-of-Systems, a new way to see systems

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Who am I?

30+ years of experience:
> 5 years in the “NTIC”: Networks, telecoms, compilers and language theory, simulation.

20 years in development of systems:
> Radar: signal processing, data processing and hardware architecture
> Integrated Modular Avionics (ARINC, ASAAC)
> Electronic Warfare: architecture and Domain Design Authority
> Systems of Systems, Net-Centric Operation and Network-Centric Warfare: Architecture and Principles

Current position:
> Coauthor of the Thales Systems Engineering Methodology (Sys-EM)
> AFIS Technical Director and INCOSE CAB representative
> Convener on standardization works: ISO, AFNOR, EDA, NATO
> Coach and Trainer for Architecture and Operational Concepts (Thales and externally)
Thales Global Presence

Employees
61,000

Global presence
56 countries

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Technical Directorate, System Domain
Thales Businesses

EACH OF THE MARKETS THAT THALES SERVES PLAYS A VITAL ROLE IN SOCIETY.

AEROSPACE

SPACE

GROUND TRANSPORTATION

DEFENCE

SECURITY

€ 13 billion euros

Self-funded R&D

675 million euros
Aims of the presentation

- Why to care about Systems of Systems (SoS), even if working on “simple” products or systems.
- The added value of the SoS approach
- The SoS pain points and challenges (opportunities for research!)
Agenda (45’)

- “Well-known” examples of large Systems of Systems
- Definitions: Product, System, System of Systems, Solution
- Characteristics and classifications of SoS
- Systems Engineering principles for SoS
- Focus of modelling and Architecture Frameworks
- SoS approach for products and systems
- Paint points and challenges regarding SoS
- Conclusion
An example with Air Operations (Source: SESAR)

Make several systems working together and get synergy towards common objectives: end-to-end services, traffic, energy, time, etc.

Implementation of SoS is already started [more or less known as such]

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Military operation (Source: US-DoD)
Global Earth Observation (Source: ESA)
Interdependence between Domains in Societal SoS

(Source: T-AREA-soS)

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Definitions

Product:

➢ Result of a process. [Source: ISO/IEC 15939:2007]

➢ A Product is intended to be sold, directly or indirectly (internal product) to customers for satisfying their expectations and meeting their operational requirements. A Product can be a hardware or software equipment or a service or a system or a generic solution. [Source: Thales]

System:

➢ Combination of interacting elements organized to achieve one or more stated purposes. 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. [Source: INCOSE]

Solution scope:

➢ The solution covers not only the development of the operational system but also the enabling products: system for designing, producing, installing the operational system (e.g., test resources), support system (system supporting the operational system, e.g., training, distribution and repair network). [Source: Thales]
In this example, we develop and sell buses.
Any element necessary to understand the product in its environment, over its life cycle (Systemic Approach).

Note: The Operators (Driver(s)) are part of the system.
Any enabling system sustaining the system of interest over its life cycle: development system, delivery system, maintenance system, etc.
Be careful about the different scopes of solution.
What is a System of Systems?

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

Note: Any of the constituent systems could be an SoS

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Some agreed bases... but far from being formal

MAIER’s criteria
- Operational independence of the component systems
- Managerial independence of the component systems
- Evolutionary development
- Emergent behavior
- Geographic distribution (no shared resource)

Considering criteria dependencies
- Evolutionary development is a consequence of integration of independent component systems
- Emergent behavior is a consequence of operation of independent component systems
- Resource segregation is required for independent systems

Pain points are:
- Operational independence → interoperability
- Managerial independence → Project management and Systems Engineering

Need for research!
Some agreed bases… but far from being formal

MAIER’s criteria
- Operational independence of the component systems
- Managerial independence of the component systems
- Evolutionary development
- Emergent behavior
- Geographic distribution (*no shared resource*)

In reality: never totally satisfied

John Boardman & Brian Sauser “System of Systems – the meaning of of”
- Autonomy (independence) vs Belonging to SoS
- Geographical distribution VS Connectivity
- Diversity & Emergence VS SoS objectives

Compromise have to be got
SoS-Specific developments

Federation / Orchestration Management System

• • • • • • •

Constituent systems

SoS Constituent mediation adaptors

SoS Infrastructure / Connectivity

E.g. See NATO NC3 taxonomy and NISP (unclassified) and NCOIC

Major problems

• Doctrines

• Semantic

• Protocols

• Interfaces
One of the proposed classifications

Virtual SoS

Collaborative SoS

Acknowledged SoS

Directed SoS

Based on Dahmann & Baldwin, 2008
Another Classification from the French MOD

Management styles (how to get them?)

Single [complex] system

Directed

Local

Global

Centralised

Shared

Set of Interoperating systems

Individual

Various types of SoS have to be considered

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## SoS Engineering Key Concepts

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Traditional Systems Engineering</th>
<th>System-of-Systems Engineering</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Development of single system to meet stakeholder requirements and defined performance</td>
<td>Evolving new system-of-systems capability by leveraging synergies of legacy systems</td>
</tr>
<tr>
<td>System Architecture</td>
<td>System architecture established early in lifecycle and remains relatively stable</td>
<td>Dynamic reconfiguration of architecture as needs change; use of service oriented architecture approach as enabler</td>
</tr>
<tr>
<td>System Interoperability</td>
<td>Defines and implements specific interface requirements to integrate components in system</td>
<td>Component systems can operate independently of SoS in a useful manner. Protocols and Standards essential to enable interoperable systems</td>
</tr>
<tr>
<td>System “illities”</td>
<td>Reliability, Maintainability, Availability are typical illities</td>
<td>Added “illities” such as flexibility, adaptability, composability</td>
</tr>
<tr>
<td>Acquisition and Management</td>
<td>Centralized acquisition and management of the system</td>
<td>Component systems separately acquired and continue to be managed as independent systems</td>
</tr>
<tr>
<td>Anticipation of Needs</td>
<td>Concept phase activity to determine system needs.</td>
<td>Intense concept phase analysis followed by continuous anticipation, aided by ongoing experimentation</td>
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With “Agile” approach, Systems Engineering will move towards SoS Engineering!
SoS System Engineering Steps and cycles


- Monitoring and Assessing Potential Impacts of Changes on SoS Performance
- Orchestrating Upgrades to SoS
- Assessing Performance to Capabilities Objectives
- Translating Capability Objective
- Translating into High-Level SoS Requirements
- Developing, Evolving and Maintaining an Architecture for the SoS
- Understanding Systems and Relationships
- Coordinate, monitor and facilitate systems’ development, test and evaluation
- Process validation
- Capability assessment
- Sets of systems Integration Verification & validation
- System Characterisation

Operational Process Definition
System Capability Definition
Identification of candidate systems
Negotiation with systems
Plan development

Independent Systems Engineering and Operations

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Strong need for evolution of the S.E. standards to deal with SoS

Main Systems Engineering reference documents:
- ISO/IEC/IEEE 15288 Systems and software engineering — System life cycle processes
- ISO/IEC/IEEE 15289 Systems and software engineering — Content of life-cycle information products
- ISO/IEC 24748 Systems and software engineering — Life cycle management
- INCOSE Systems Engineering Handbook

A handbook is available in the Thales Reference System to provide guidance on SoS
Main models to be considered for SoS
Architecture Frameworks: NATO example

- **NATO Capability View**: Documents the strategic picture of how military capability is evolving in order to support capability management and equipment planning.

- **NATO Operational View**: Documents the operational processes, relationships and context to support operational analyses and requirements development.

- **NATO System View**: Documents system functionality and interconnectivity to support system analysis and through life management.

- **NATO Technical View**: Documents policy, standards, guidance and constraints to specify and assure quality expectations.

- **NATO Program View**: Documents programme dependencies, timelines and status to inform programme management and procurement synchronization.

- **NATO Services View**: Documents Services functionality, constraints and interoperability.

- **Human Factors View**: Documents Human Concepts, Constraints, Functions, Roles, Human Networks, Training, and Metrics.

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Human views: Adaptation of UK-MOD and NATO works

NSV-8
NSV-9

System and Technology evolution

HV-B Constraints

Concepts of Operations
NOV-1

HV-E Human Network

Communication

Needlines

Interoperability

NSV-3

NSV-6

Exchange

HV-F Training

Exchanges

NOV-2

NOV-3

NOV-4

Organisation

HV-D Roles

NOV-5

Behaviour

NOV-6

NSV-7

Quality Requirements

NSV-10

Rules, States and modes

руж

NSV-4

NSV-5

Functions and activities

HV-G Metrics

HV-C Tasks
Let's consider this

And also this

Or this
SoS criteria apply to products (systems)

Do you think the provider master the life cycle of the components?
> Operating systems Windows, Linux, Android, etc
> Devices (disk drive, hardware plug-ins, etc).

Call this “managerial independence”

Do you think we master the life cycle of the applicative components?
> Office tools
> On-board and off-boards apps.

Call this “Operational independence”

SoS approach is a way to better understand problems in products and systems:
> Emergent behavior
> Evolutionary development
> Dependability (segregation resources and functions)

Maier’s criteria also work for products!

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SoS approach is a way to better understand multi-systemic composition

Each of the major product parts can be studied with a systemic approach. i.e. Combination of interacting elements organized to achieve one or more stated purposes. 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 [see INCOSE definition]
SoS approach is a way to better understand multi-systemic composition

- Product parts can be studied with a systemic approach:
  > Driving system
  > Energy system
  > Propulsion system
  > Breaking system
  > Navigation system
  > Multi-media system
  > Etc.

- SoS criteria allow refining the operational analysis, WBS, OBS & PBS.
SoS approach is a way to better understand multi-systemic composition

Product parts can be studied with a systemic approach:
- Driving system
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- Etc.

SoS criteria allow refining the operational analysis, WBS, OBS & PBS.

SoS approach could be a way to secure the development and operations:
I.e. to prevent emerging problem, dependability, etc.

Example 1: after Jeep hack, Chrysler recalls 1.4 M vehicles for bug fix.

Example 2: In a car, battery is a single point of failure: breakdown consequence? Why not having two?
SoS approach is a way to better understand the PLM challenges

<table>
<thead>
<tr>
<th></th>
<th>System 1</th>
<th>System 2</th>
<th>System 3</th>
<th>System 4</th>
<th>System ..</th>
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<tbody>
<tr>
<td>Product A</td>
<td>Usage /</td>
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<td>System Life-cycle</td>
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<tr>
<td>Product B</td>
<td>Period 1</td>
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<td>Period 4</td>
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<td>Product C</td>
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<td>Product ..</td>
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Life-cycles of the systems are transverse to the life-cycles of the reused products.
N-P complexity problem.
### Main challenges identifies for SoS development

(Source: Thales)

<table>
<thead>
<tr>
<th>Challenges</th>
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</thead>
<tbody>
<tr>
<td>1- Contracting of SoS dynamically defined</td>
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<tr>
<td>2- Multi-layer agile Systems Engineering and agile SoS breakdown</td>
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<tr>
<td>3- Dynamic loose coupling and (re)configuration of constituent systems</td>
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<tr>
<td>4- Flexible paradigms for interaction (mix of services, artefacts, events and streams)</td>
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<tr>
<td>5- Behaviour (multi-level consistent scheduling + non-functional properties)</td>
</tr>
<tr>
<td>6- Multi-level life cycles management</td>
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<tr>
<td>7- Engineering process to meet both bottom-up; top-down; dynamic system insertion/removal; legacy alignment</td>
</tr>
<tr>
<td>8- Run-time Management, Integrated logistic support and training on SoS or system built dynamically</td>
</tr>
<tr>
<td>9- Modelling and simulation to estimate feasibility, forecast behaviour and provide a reference for management</td>
</tr>
</tbody>
</table>
4 main European support actions on SoS

**T-Area-SoS:**
- Towards a SoS roadmap
- Supply-side driven
- Top-Down approach
- Systems Engineering
- US-EU

**Road2SoS:**
- Towards a SoS roadmap
- Sector/demand-side driven
- Bottom-up approach
- Consulting industry experts
- Use cases: Energy, Manufacturing, Crisis Management, Traffic Control

**Danse:**
- Designing for adaptability and evolution in SoS Engineering
- SoS engineering approaches
- Use cases: Air Traffic Management; Autonomous Ground Transportation; Water Treatment and Supply

**Compass**
- Comprehensive Modelling for Advanced Systems of Systems
- Model-Based tools
- Use cases: Emergency Response; Audio/Video/Home; Automation Ecosystem; Integrated Modular Avionics.

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https://www.tareasos.eu/  
http://www.road2sos-project.eu  
http://www.danse-ip.eu/home/  
http://www.compass-research.eu/
Conclusion

- **Systems of Systems**
  - Literature gives the main principles about Systems Engineering of SoS
  - Systems of Systems are now characterised
  - Architecture Frameworks strongly help for SoS Systems Engineering
  - Major pain points remain about SoS

- **SoS approach is also valid for product development**
  - Systems using products might be engineered with an SoS approach
  - Systems Engineering will move towards the SoS approach → Agile SE and SE with multiple Life cycle management.

- **Many research opportunities exist…**
  - But, need focus on the right problems
If you are interested in Systems Engineering of SoS:

- INCOSE SoS Working Group
- ISO JTC1/SC7 SoS Study Group
- AFIS “3S-AI” Technical Committee