

Systems of Systems

Escuela de Arquitectura,
Ingeniería y Diseño

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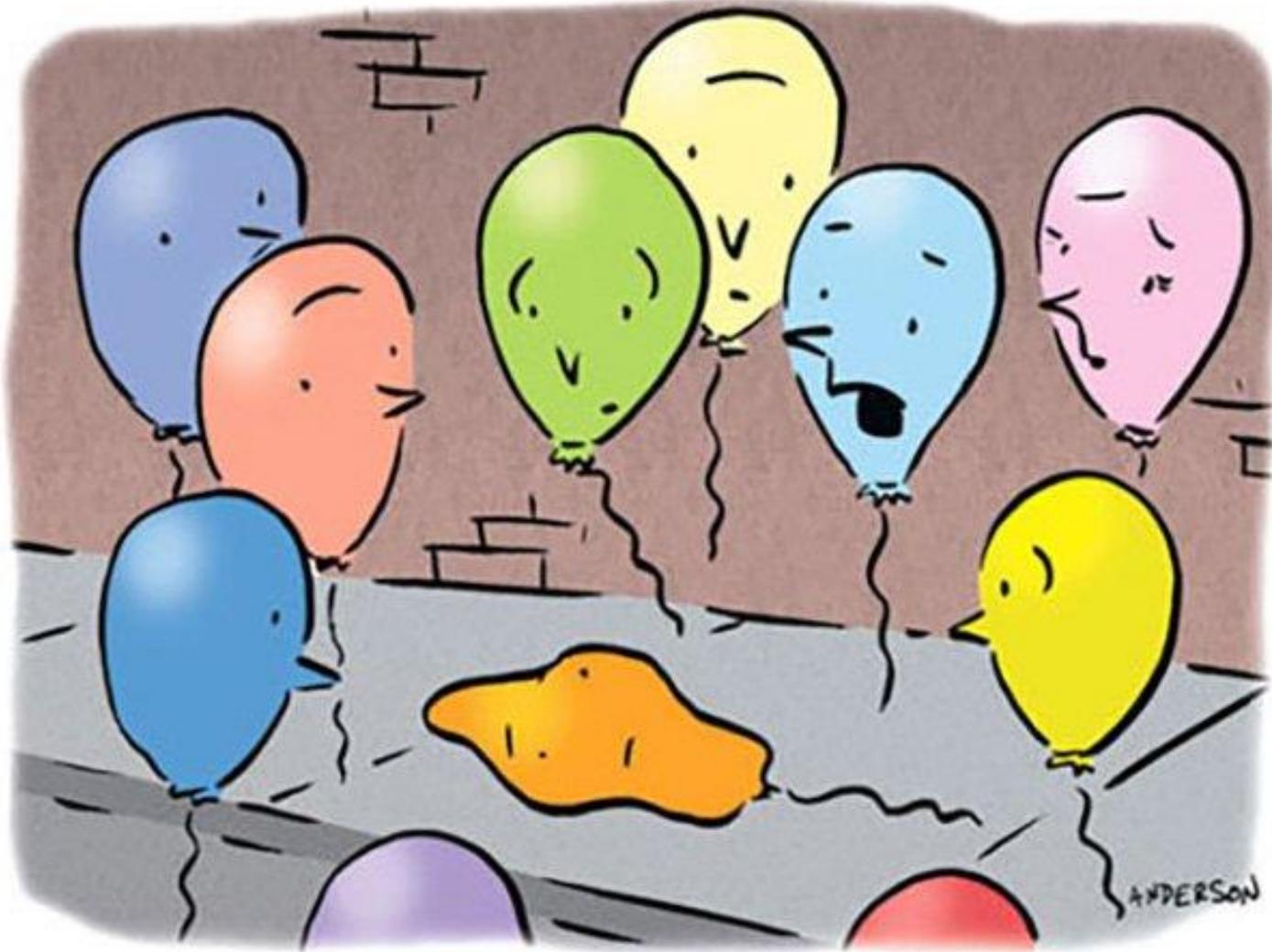
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Just a pun?



Systems



"Everyone back! Give him some air!"

Systems of Systems

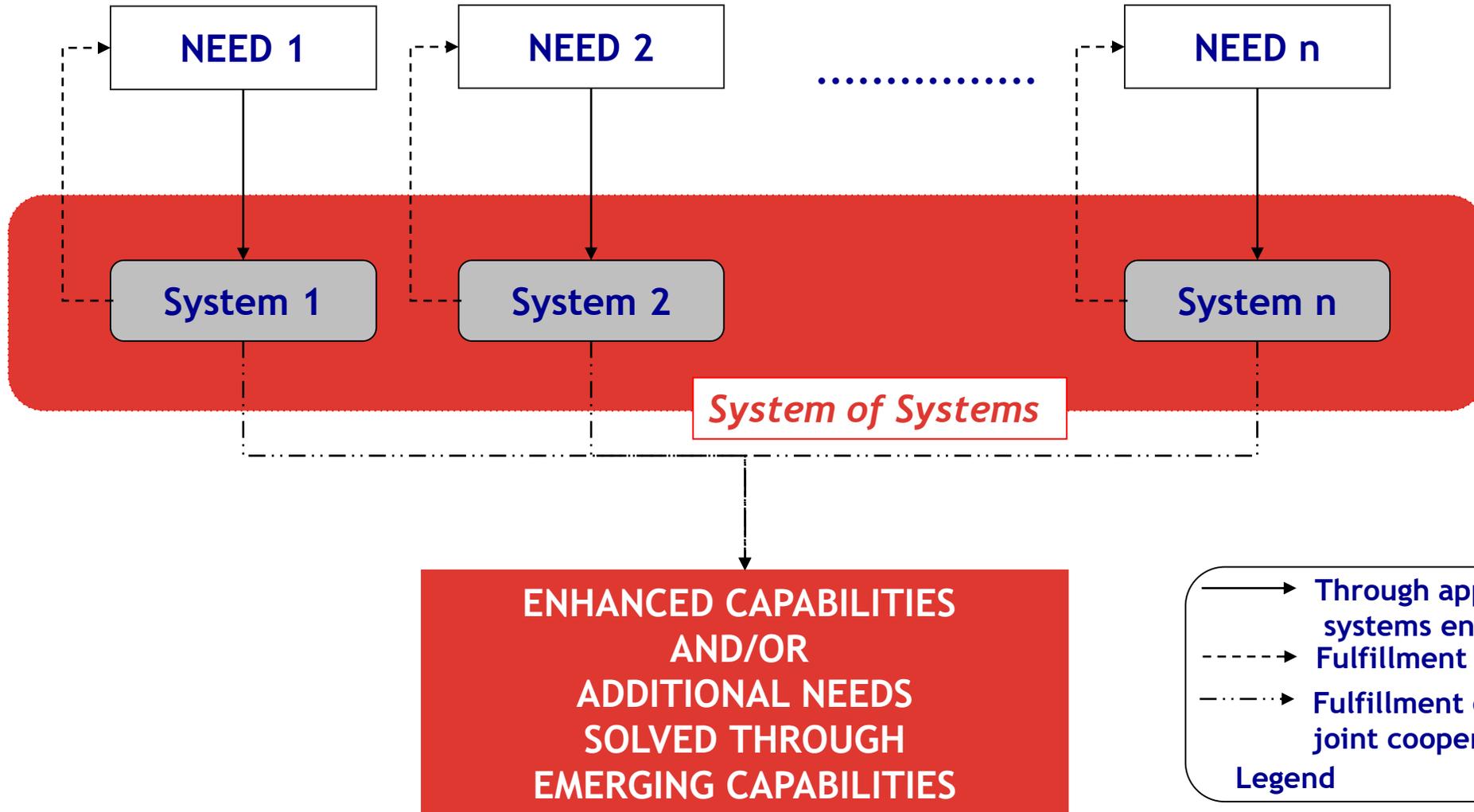
Federations of Systems

Systems, and families of systems



- A system is a set of elements to work together and that, duly inter-related, contribute to the achievement of a certain goal.
- A federation of systems is a set of systems that do not have any interaction with each other, but that are somehow related in purpose or functionality and that can be used collectively.
- A System of Systems (SoS) is a system integrated by entities that are each of them systems in their own right and that can work separately and independently, although by working in combination with the rest of the systems or entities they are collectively capable of achieving goals that none of them could separately attain.

Systems of Systems



Systems versus Systems of Systems (*Boardman and Sauser*)



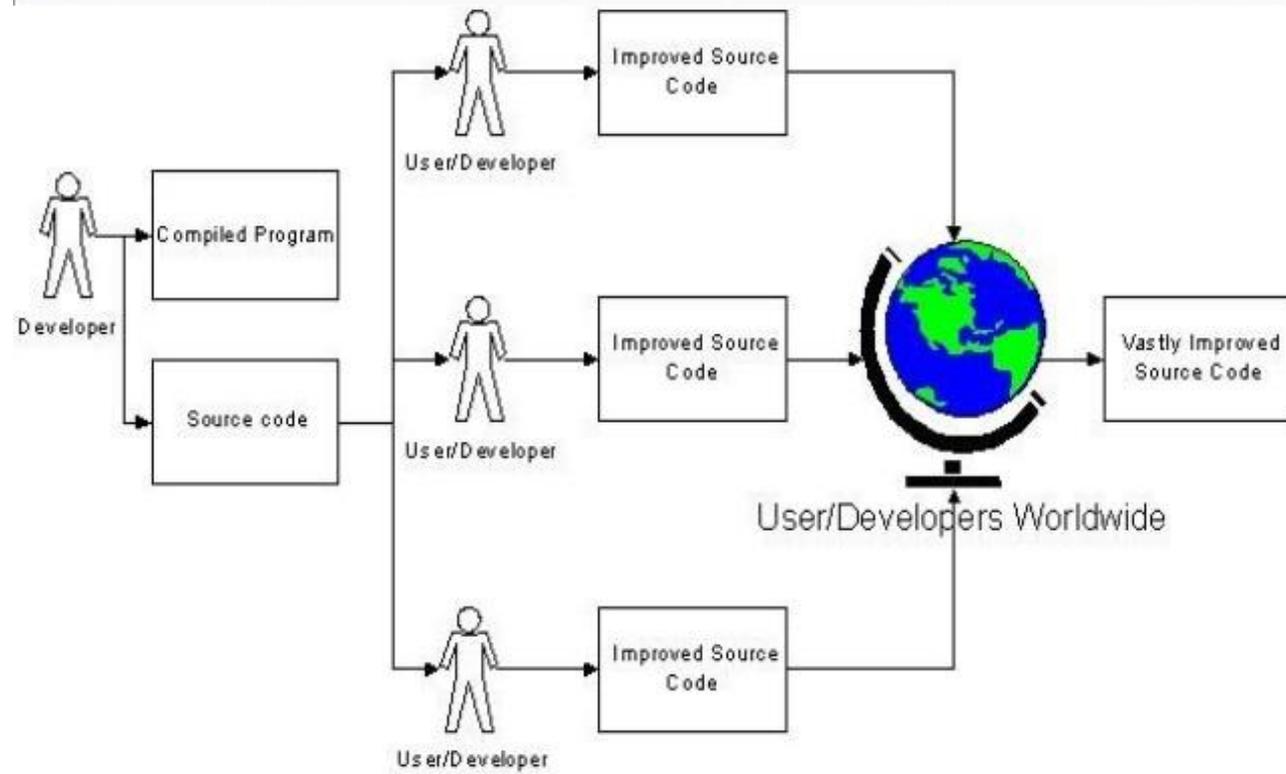
Characteristic	Concept	System	System of Systems (SoS)
Autonomy	The ability to make independent choices.	Each system element yields its autonomy to the system.	Each system essentially retains its autonomy, in spite of its working together with other systems of the SoS.
Belonging	Quality of being integral part of something.	The elements do not have the choice of deciding about their belonging to the system.	The belonging of each system to a SoS has to be negotiated and accepted.
Connectivity	Quality of bonding, linking parts of a system.	Relationships among system elements are designed simultaneously with the own system elements.	The relationships among the systems of a SoS emerge as a consequence of their inter-relationships.
Diversity	Heterogeneity	System diversity is due to the nature of the elements required for the system to accomplish its goals.	Diversity gives more capacity and resilience to a SoS.
Emergence	Quality of raise from, or have origin in, other thing.	The concepts of emergence and system go together. The qualities that emerge on a system are fixed.	The qualities that emerge on a SoS are dynamic, as is the boundary of the SoS, by definition.

Types of Systems of Systems



Type of SoS	Definition
Virtual	Lacks a central management authority and a centrally agreed-upon-purpose. Large-scale behavior emerges but this type of SoS must rely on relatively invisible mechanisms to maintain it.
Collaborative	The component systems interact more or less voluntarily to fulfill agreed upon central purposes.
Acknowledged	Has recognized objectives, a designated manager, and resources. However, the constituent systems retain their independent ownership, objectives, funding, development, and sustainment approaches. Changes in the systems are based on collaboration between the SoS and the system.
Directed	The SoS is built and managed to fulfill specific purposes. It is centrally managed during long-term operation to continue to fulfill those purposes. The component systems maintain an ability to operate independently, but their normal operational mode is subordinated to the central managed purpose.

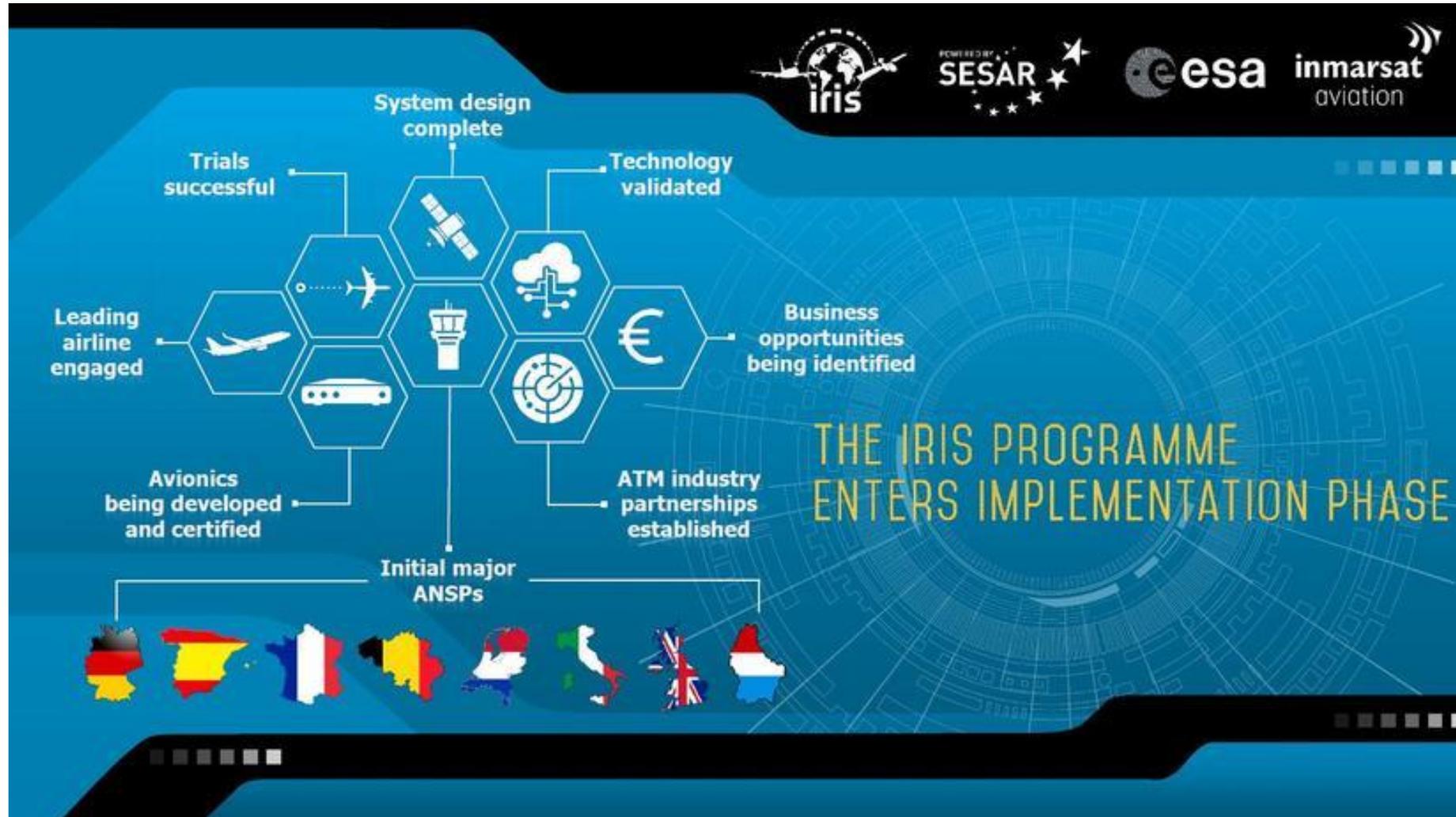
HOW OPEN SOURCE WORKS ?



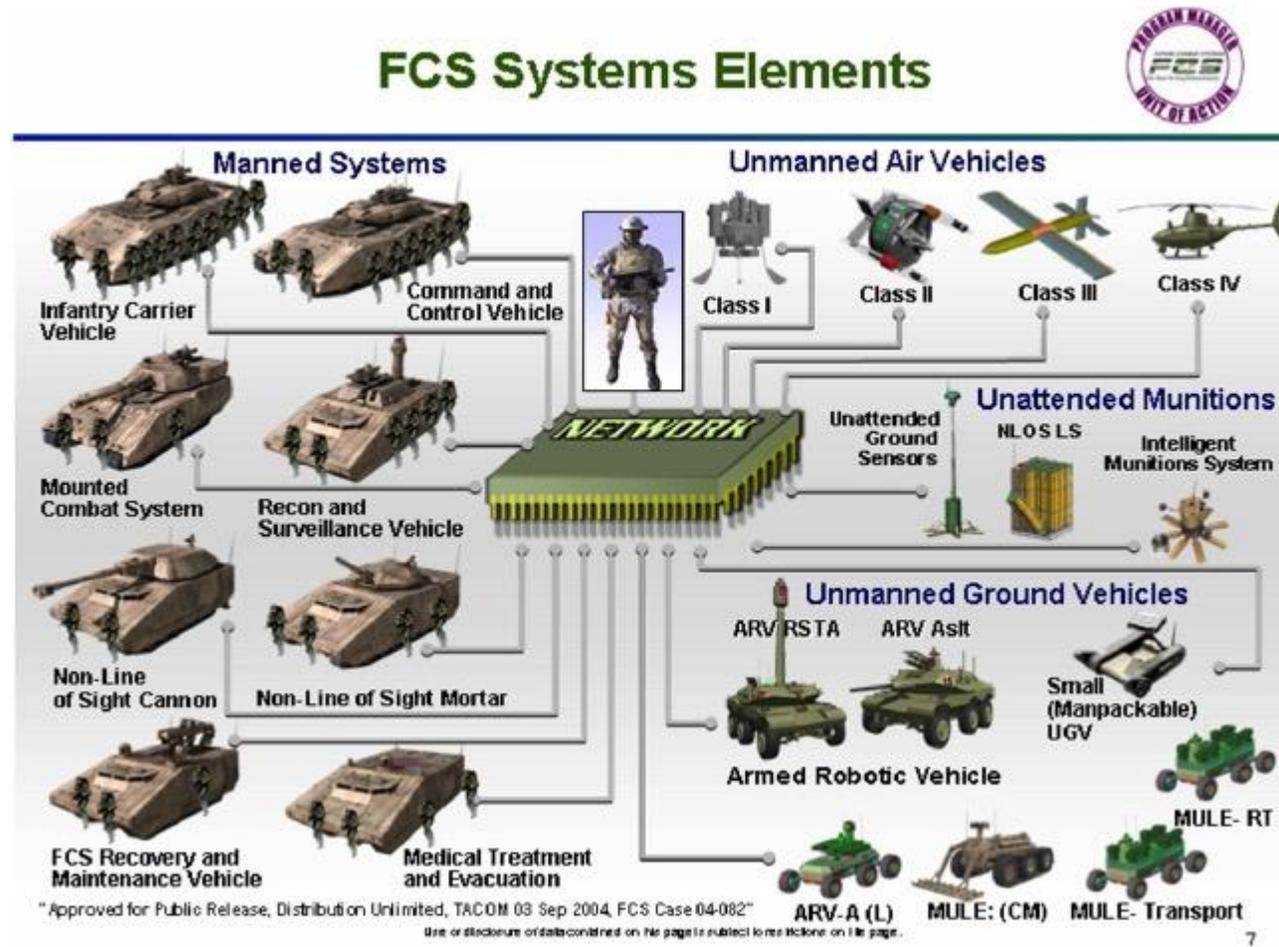
Collaborative System of Systems



Acknowledged System of Systems



Directed System of Systems



From directed, to collaborative System of Systems



Complex systems, and systems of systems



Many systems are complex, but that doesn't make them system of systems.

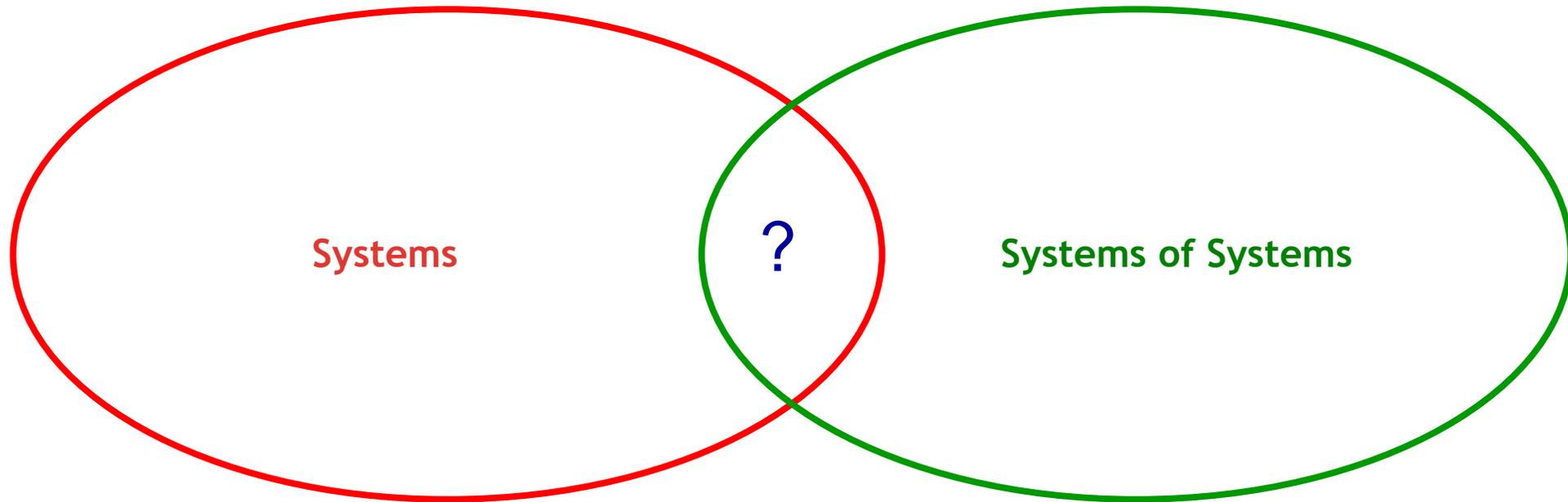


A riddle



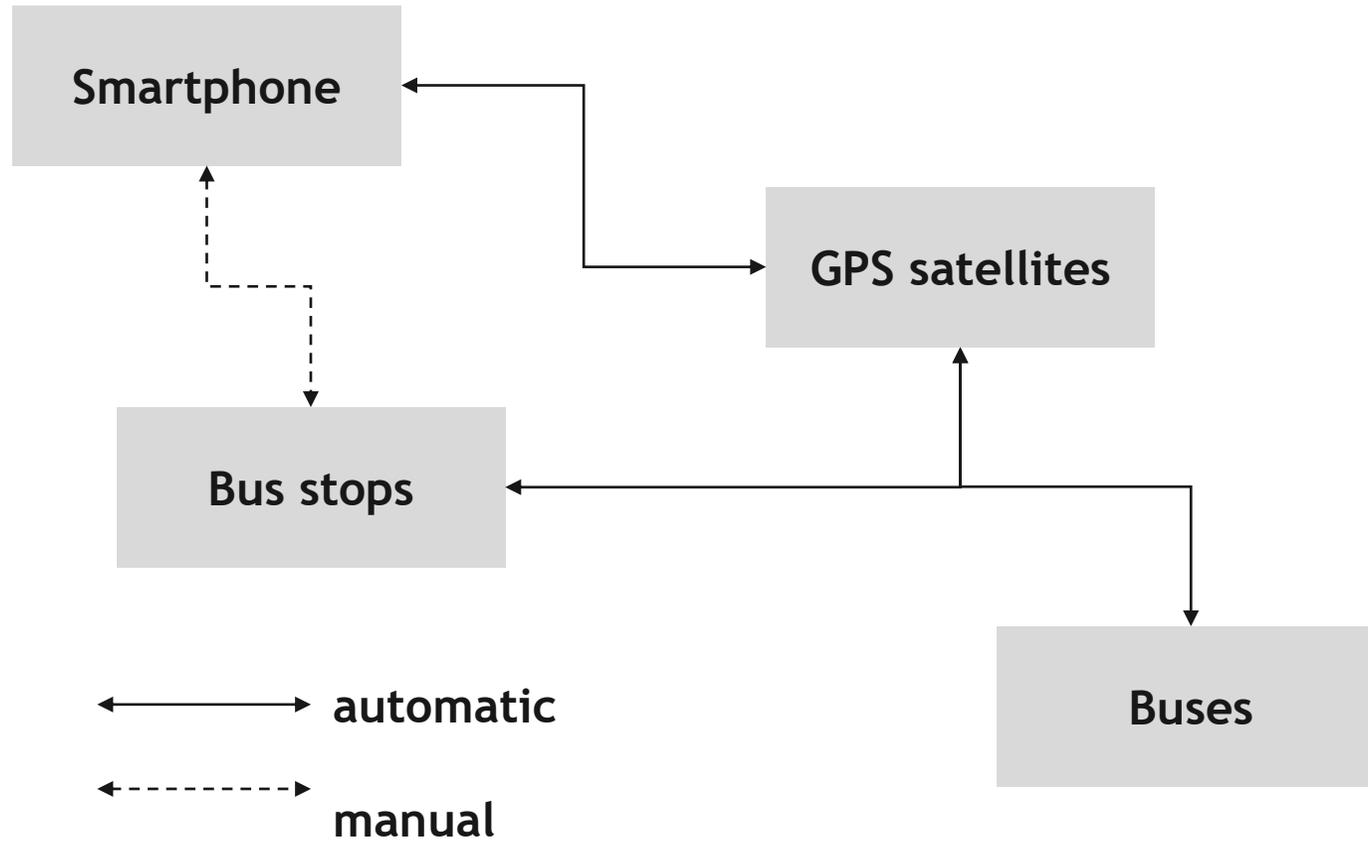
Consider a car designed to use GPS signals for navigation, radio broadcasts for entertaining, traffic broadcasts for safety and information, ... Is it a (complex) system, a system of systems, or what?

Fuzzy boundaries

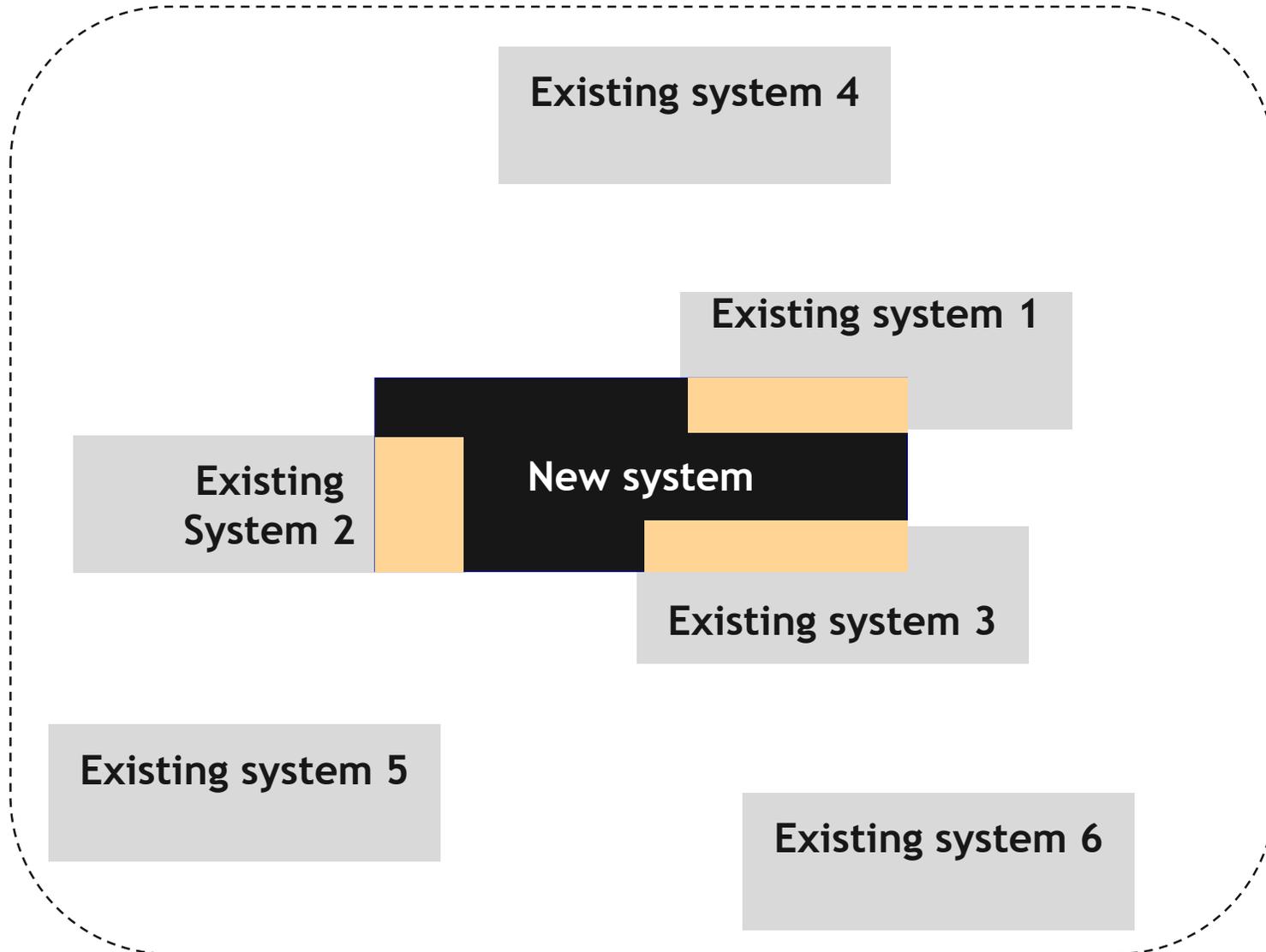


The frontier between ordinary systems and systems of systems is not always easy to establish. It will always be possible to think of cases difficult to classify. Yet, that difficulty is not that important as, regarding their design and development, the systems engineering framework holds true for both!

Interfaces



Borrowed capabilities and emerging capabilities



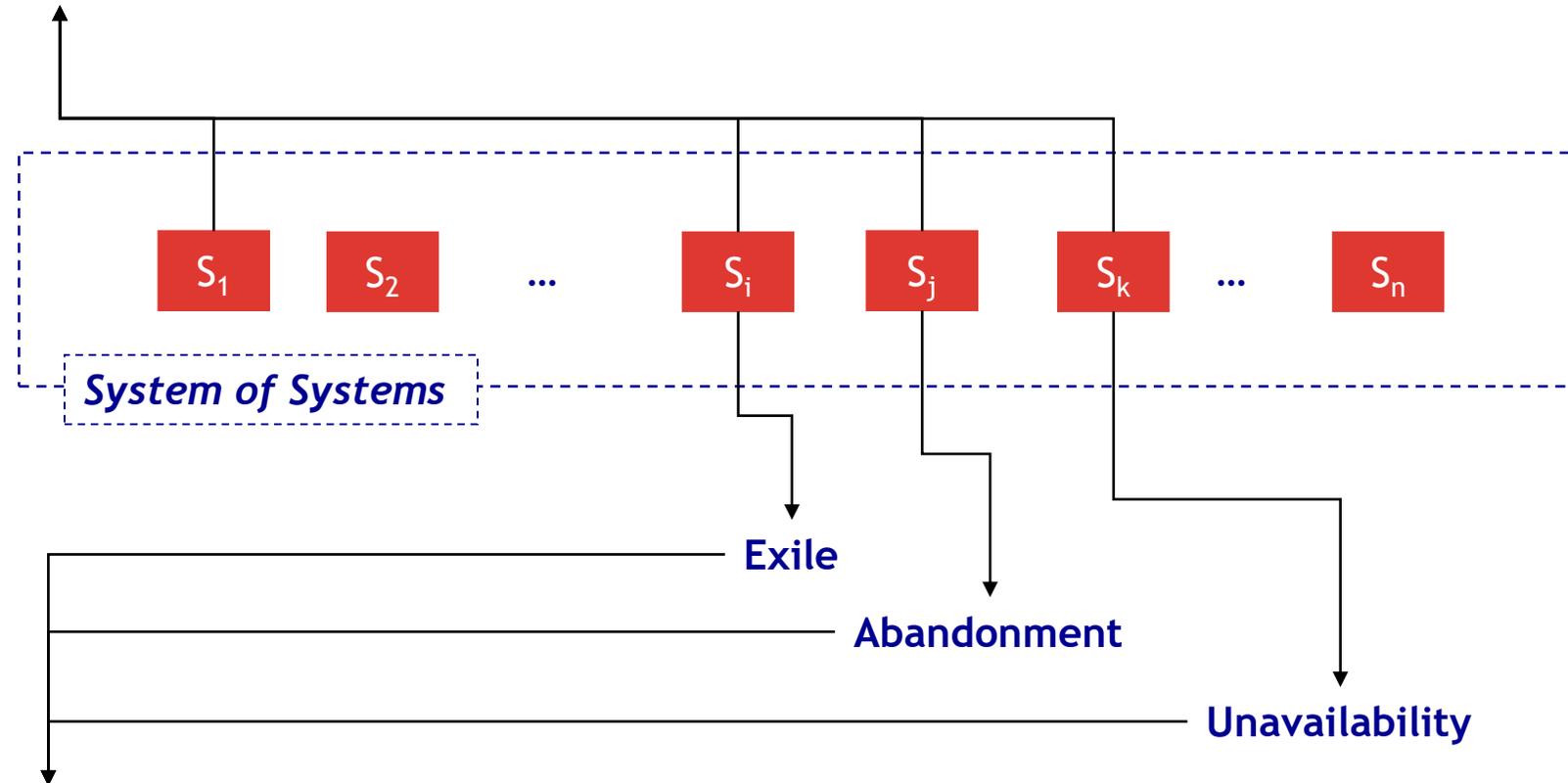
- Many Systems of Systems are either Collaborative or Acknowledged.
- It is important to differentiate between borrowed and emerging capabilities; the former may simplify the design of the new system, whereas the latter are what makes the family a system of systems.

- When designing a system to create and/or to join a Systems of Systems, as important as considering potential design concepts is to consider what capabilities could be borrowed from other existing systems.
- That will have an impact in the solution space, due to both the capabilities to be borrowed and the necessary interfaces to ensure communication between the systems.

Emerging and receding capabilities



S_1 experiences an emerging capability



S_1 experiences a receding capability

When designing a system to create and/or to join a Systems of Systems, as important as considering the emerging capabilities is taking into account the potentially receding ones.

Definitions and metrics: Systems, and Systems of Systems



SYSTEM

EFFECTIVENESS

LIFE-CYCLE COST

Operational availability
Operational reliability
Logistics footprint
Response time

Cost per unit of use
Life-cycle cost per unit of use

Reliability

Maintainability

Supportability

SYSTEM OF SYSTEMS

Definitions

Metrics

Notional cases

Case studies

Receding Capabilities in Systems of Systems

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Abstract—Systems of systems are characterized by their dynamic behavior, exhibiting evolving emerging capabilities as new members join the family. Yet, little has been said on the possibility of some members leaving the system of systems, with the impact that it might have on the emerging capabilities experienced by some members of the family. At the same time, growing attention is given to the need for establishing a sound foundation for the field of systems engineering, with the development of the appropriate theories and methods, which require effectiveness definitions and metrics, among others. This paper introduces the concept of receding capabilities of a system of system, as a necessary building block to further complement and develop the foundation of systems engineering. The necessary concepts are defined and a proposed formulation is presented to capture the likelihood and impact of receding capabilities. A notional example is presented to illustrate the presented concepts.

Keywords—receding; capabilities; system of systems.

I. SYSTEMS AND SYSTEMS OF SYSTEMS

Systems are designed to fulfill either a need that is identified by an end customer or a perceived market opportunity. Systems engineering is the interdisciplinary approach and means to enable the realization of successful systems [1]. The systems engineering framework is the set of assumptions, concepts, values, methods and processes that constitutes the systems approach to the design and development of systems that fulfill perceived needs or opportunities throughout their entire operational lives [2]. Systems have grown exponentially in complexity, leading to large systems that are actually integrated by a variety of component systems, whether they are newly engineered systems, potentially tailored existing Commercial-Off-The-Shelf [COTS] systems, and/or legacy systems. The term System of Systems (SoS) has become the standard to describe them [3,4]. Systems of systems are one of two types of families of systems, of which the other one are the Federations of Systems (FoS) [5]. A set of systems is called a family of systems if there is some type of relationship between them, whether in the nature of their end purpose or in their capability of co-operating together, yielding emergent capabilities. A system of systems (SoS) is a system integrated by entities that are each of them systems in their own right and that can work separately and independently, although by working together they are collectively capable of achieving goals that none of them could separately attain [6]. An SoS can be defined also as

a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities [7]. An SoS has also been defined as System of Interest (SoI) whose elements are managerially and/or operationally independent systems [1]. Some attributes are meaningful at certain scales and meaningless at lower scales [8]. Systems exhibit emergent properties, as they possess attributes that none of its component elements has. Similarly, an SoS has emergent capabilities and the cooperation among component systems enables the accomplishment of goals that no component system alone could achieve. Table I shows the main differences between systems and systems of systems [9].

TABLE I. SYSTEMS VS. SYSTEMS OF SYSTEMS (extracted from [9]).

Characteristic	System	System of Systems
Autonomy	Each system element yields its autonomy to the system.	Each system essentially retains its autonomy, in spite of its working together with other systems of the SoS.
Belonging	The elements do not have the choice of deciding about their belonging to the system.	The belonging of each system to an SoS has to be negotiated and accepted.
Connectivity	Relationships among system elements are designed simultaneously with the own system elements.	The relationships among the systems of an SoS emerge as a consequence of their inter-relationships.
Diversity	System diversity is due to the nature of the elements required for the system to accomplish its goals.	Diversity gives more capacity and resilience to an SoS.
Emergence	The qualities that emerge on a system are fixed.	The qualities that emerge on an SoS are dynamic, as is the boundary of the SoS.

OPERATIONAL AVAILABILITY AND OPERATIONAL RELIABILITY METRICS OF THE EMERGING CAPABILITIES OF SYSTEMS OF SYSTEMS

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Abstract

There is a significant amount of literature on system effectiveness, mainly addressing operational availability and operational reliability. Today's systems are more and more inter-connected, yielding emerging capabilities. Despite the growing relevance and presence of systems of systems, little has been done in the development of metrics to assess the effectiveness of systems of systems. Without the appropriate metrics that are duly defined and are quantifiable, it is much more difficult to establish the needed non-functional requirements on system effectiveness, to perform the necessary assessments that can influence the design efforts, or to validate actual effectiveness in the operational life. This paper proposes a comprehensive model to assess the operational availability and the operational reliability of systems of systems. Definitions for the proposed metrics are given and the mathematical model for their prediction is shown. An example is provided to illustrate the applicability of the proposed model.

Keywords

system of systems, operational, availability, reliability, metrics

Introduction

Systems are designed to fulfill either a need that is identified by an end customer or a perceived market opportunity. Although the definition of system is broad enough to encompass any human design and development effort, there are cases that deserve special denominations. A series of systems is called a family of systems if there is some type of relationship between them, whether in the nature of their end purpose or in their capability of co-operating together, yielding emergent capabilities. Two families of systems are the federations of systems and the systems of systems (SoS) (Sage & Cuppan, 2001). In an SoS, individual needs are satisfied with their corresponding systems. The interactions and cooperation among them enables the fulfilling of additional needs, as a result of the emergent capabilities, as shown in Exhibit 1 (Sols, 2014).

An SoS is a system integrated by entities that are each of them systems in their own right and that can work separately and independently, although by working together they are collectively capable of achieving goals that none of them could separately attain (Maier, 1998). An SoS can be defined also as a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities (DoD, 2004). A system of systems is a system of interest whose elements are managerially and/or operationally independent systems (INCOSE, 2015).

There are four different types of SoS: virtual, collaborative, acknowledged and directed (MITRE, 2014). The component systems of an SoS may have different ownership and/or management, as shown in Exhibit 2. The distinction is relevant for the purpose of assessing the effectiveness of an SoS, as a function of the effectiveness of its component systems. In the case of a virtual or a collaborative SoS the decisions taken by the different owners of the component systems will clearly affect the emerging capabilities that require their concurrence. In an acknowledged SoS the existence of a coordinated management the negative impact on emerging capabilities as a result of decisions taken by system owners is less likely, due to the joint ownership and/or coordinated management. Such likelihood is far less in the case of a directed SoS. It is worth noticing that the members of an SoS may be unavailable not only due to technical reasons, such as failures that need to be corrected or planned, preventive maintenance that is no compatible with system utilization. The members of the family may decide to leave it voluntarily, or be forced to doing so. If they choose to abandon the system the act is called abandonment (Salado, 2015). If on the other hand it is some of members of the family who decide to expel a system from the system of systems, the situation is called exile (Salado, 2016). Therefore, if in all SoS a component system may be temporarily

LOONEY TUNES



"That's all Folks!"