

Are Systems of Systems a New Reality?

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Systems theory was introduced by Bertalanffy (1949) in the 1930s based on research in biology with a focus on organisms as a whole, including their complex organisation and physiological functions. Very rapidly, the notion of systems became popular in different fields: *“Systems thinking plays a dominant role in a wide range of fields from industrial enterprise and armaments to esoteric topics of pure science. Innumerable publications, conferences, symposia and courses are devoted to it. Professions and jobs have appeared in recent years which, unknown a short while ago, go under names such as systems design, systems analysis, systems engineering (SE) and others.”* (Bertalanffy, 1968, p. 3) The systems theory approaches phenomena as a whole and no longer as an addition of parts: *“It is necessary to study not only parts and processes in isolation, but also to solve the decisive problems found in organization and order unifying them, resulting from dynamic interaction of parts, and making the behaviour of the parts different when studied in isolation or within the whole...”* Bertalanffy (1968, p. 31). In line with Bertalanffy's works, exemplified by the International Society for the Systems Science (2007), a new scientific field of Systems theory emerged.

With the development of computers in the 1960s and 1970s, technological systems became more and more complex. Increasing complexity in combination with the integration of several systems led to the notion of interaction of parts between Systems and its elements, which opened the way for the concept of System of Systems (SoS) in the 1970s. In economy the notion is used as follow *“the concepts and terms commonly used to talk about systems have not themselves been organized into systems.”* (Russell, 1971, p. 661) In the 1990s, the notion of Systems of Systems spread and was for instance defined as: *“[...] largescale integrated systems that are heterogeneous and independently operable on their own, but are networked together for a common goal.”* (Jamshidi, 2009, p. 2). Some important differences between systems and Systems of Systems are highlighted by Jamshidi (2009, pp. 2-3) *“Systems of Systems exist when there is a presence of a majority of the following five characteristics: operational and managerial independence, geographic distribution, emergent behaviour, and evolutionary development.”* This notion of SoS was used in different fields, especially in the defence industry, but also when dealing with very sophisticated technological systems, such as the Boeing 787. Indeed Systems of Systems are claimed to improve the way of understanding complex systems or increase the potential for SoS to enhance the effectiveness of large and complex systems. But it gave rise to controversies. It is also

System of Systems Engineering (SoSE) that manages the integration of systems into SoS. This also means that traditional Systems Engineering, managing traditional systems, should evolve into SoSE in order to manage SoS.

The aim of the paper is to give an account of these controversies and to answer the question: are Systems of Systems something new and have they made a valuable contribution to Systems theory since its inception?

We will first give a few examples and then describe the notion and attempt to describe the characteristics of Systems of Systems. Next, we will discuss the current controversies and finally come to a conclusion.

Ants, ecosystems, air traffic systems and the Future Combat System as Systems of Systems

Examples of SoS can be found in nature and in technological systems and can be perceived in a continuum with different degrees of sophistication. Jamshidi (2009, p. 3) argues that in nature ant colonies can be considered as ad-hoc and simple SoS whereas other biological ecosystems, living organisms or human colonies are examples of SoS with much more sophistication and complexity. A number of essential principles control the natural SoS, which are synergetic or holistic relationships; open interfaces like permeable boundaries; conservation or least amount of waste; modularity or self-containment and encapsulation; self-governance or self-organisation; emergence like emerging structure and behaviour; symbiosis or mutual self-rewarding relationships and reconfigurability which is the ability to change and adapt. By following these principles Azani (2009, pp. 25-32) explains that an open SoS can be flexible and efficient and can thus survive.

Human-built SoS can contain considerable amounts of complex technology which adds to the complexity compared to a natural SoS. The Boeing 787 program is, for instance, claimed to be a SoS interconnected in a computerized communication network which is to enhance the overall performance of the airplane but also of the entire air traffic system of which the airplane is a part. The benefits of the e-enabled airplane of Boeing 787 is said by Gosling (2009, p. 22) to be more efficient when it comes to maintenance and the costs created by administration and paper documents are decreased. Defining the airplane as a SoS means that technologies and functions are to be connected as a network. This means that passenger technologies, Cabin & Airline Services, Maintenance, Open Networking, Avionics Data and Flight Deck are to be connected. Furthermore, maintenance, materials and other ground functionalities like airlines and the Boeing Company are connected into one communication network. The system's unit of analysis is the airline but the entire air traffic system belongs to the SoS. The airplane is, in this view, a subsystem within a System of Systems. According to Wilber (2009), leveraging industrial advances in computing and network technologies were important motives to initiate this project. Using business solutions like network-centric operations and SoS engineering were the way for Boeing to reduce cost in production, operations and maintenance (Wilber, 2009, pp. 232-233). Calling it the Gold Care Maintenance Solution, the Boeing Company claims to have the ability to offer the best qualified service enabled by network centric solutions (Wilber, 2009, p. 233).

The US Army project Future Combat System (FCS) also qualifies as a SoS, although considerably more sophisticated and complex, and including manned and unmanned

vehicles connected in one communication network. The plan was to change the way the US Army would organise, train, deploy and equip its future armed forces. It was designed to consist of 18 fighting vehicle systems which were networked together and for that reason was considered more deadly, survivable, deployable and sustainable than existing combat systems. Self-sustainment and a small logistic footprint were deemed very important (Francis, 2003). The Department of Defense (2003) intended to have 10 out of the 18 unmanned vehicles for use on both ground and in the air. The project scope was ambitious since the announced objective was stated as follows: *“the FCS program will dominate the Army’s investment accounts over the next decade”* (Francis, 2003, p. 1). 22 billion dollars were allocated to the project between 2004 and 2009 and the Government Accountability Office (GAO) says in Francis’ report (2003, p. 2) that *“the acquisition strategy for the FCS is aggressive, particularly in light of the program’s vast scope.”* All parts of the US Army except the Airborne Forces and the Special Forces were to be changed into the FCS. An important economical motive claimed by The Chief of Staff of the Army and the Commander (1997, p. 18) was the potential to benefit from civil technology development– from the telecommunication industry for instance. Feickert (2005) later concludes that the FCS became very complex both regarding the vehicles but more importantly regarding the communication network. The different examples of SoS reaching from simple ant colonies to the more complex FCS do not yet explain the controversies about how SoS differ from Systems of subsystems.

Characteristics of SoS

Systems of Systems became more widely spread during the 1990s due to the increased interest in SoS from military authorities. In the US, this was defined by Sauser (2006): *“System of Systems: a computer architecture term that started in the US Military”*. Important reasons for this growing interest were the potential issues that SoS could solve and *“Reduce the Fog and Friction of War”*. As described by Owens (1996, p. 4) this was done to a large extent by technology. The overall purpose of SoS was to acquire improved results with superior effectiveness and performance. A common motive for SoS effectiveness is network technology. Indeed, military operations such as 1991’s Desert Storm unveiled the need for a better communication between different branches of the United States Armed Forces. In order to enable SoS potential and its machine interaction possibilities to perform, the system must be very fast and accurate in its interactions. Instead, if humans are involved in the interactions with machines to uphold the functionality of the system, the effectiveness of the system will be lower. Opportunities and advantages of SoS will then be lost and mistakes can easily be made (Saunders et al, 2005, pp. 2-3).

Several differences exist between SoS and traditional technological systems. First, System of Systems focus on integrating numerous independent complex systems. In that perspective, changing requirements due to new and adaptable environments can result in changing the whole development of the System of Systems. By contrast, requirements regarding traditional systems are mainly unchanged thanks to the focus on a single system aiming at an end product. Second, as a SoS changes and adapts to the environment, its architecture becomes a dominating part of its capability development. Adapting and changing SoS requires to adapt and change architecting, which complexity makes SoS differ from System of subsystems. In order to adapt to changes in requirements from, for instance, new technologies and changed technology

requirements, SoS need to be able to change and evolve constantly. Third, SoS do not have well-defined boundaries which makes it difficult to manage in a traditional way according to Wells and Sage (2009, pp. 46-47).

Further differences between SoS and System of subsystems are the constant changes that would force the SoSE activities to adapt the SoS in a timely manner. The constant changes are done with the SoS feature architecture and makes architecting of SoS different compared to System of subsystems. The architecture of SoS is about structuring the components in a system and arranging their interrelationship and evolution over time. A dynamic and flexible SoS creates a requirement for architecting that can be flexible and dynamic during an event and respond to environmental changes. Due to the dynamic and flexible behaviour, Dagli and Kilicay-Ergin (2009, pp. 77-79) claim that SoS are very difficult or impossible to long term plan, using traditional ways of measuring results. Different complex parts within the SoS have nonlinear relationships thus dramatic and sudden changes can occur unexpectedly. Short term forecasting can, however, be made for SoS since within short time frames prediction models and forecasting of behaviour can be created to support short term forecasting of SoS. Due to the SoS properties – self-arranging order, emergent order and self-organisation – SoS can according to Dagli and Kilicay-Ergin (2009, pp. 77-79) be more innovative and more adaptive than complex System of subsystems which are considered less innovative and adaptive since they are mainly focused on one or several less adaptive single systems. Innovation and adaptability are also considered important to measure a SoS, and for instance, its capability, in order to compare with other SoS or System of subsystems. Architecture is not only managing the properties mentioned above, as we will see now.

In order to understand how SoS are affected by the settings and how they are learning by proposing new ways of development, architecting is claimed to be feature best measuring performance of SoS. Measurement of SoS is necessary in order to create an understanding of the performance of a SoS. Within the architecting features' performance, risk, time and cost would be the best measurement factors for SoS according to Dagli and Kilicay-Ergin (2009, pp. 77-79) while performance regarding Systems of subsystems can be measured by their result. Also assessments of the capacity to learn the architecture and upgrade it are important factors for assessing SoS. In order to manage SoS architecting, the learning and modelling of a SoS needs to be evolutionary to be able to handle rapid transformations. Different behavioural views must be taken into account when measuring SoS, as, besides complex technology systems, dynamics due to social and cognitive processes are also involved.

Concerning Systems of subsystems efficiency, product and final solution are mostly the end goal. The dynamical behaviour will prevent any final solution or any end state. Instead, SoS have a greater focus on flexibility, extensibility and run-time interoperability. Flexibility, extensibility and run-time interoperability are therefore more important for SoS architecting. To manage evolutionary SoS, Dagli and Kilicay-Ergin claim that it is important to have an evolutionary environment in order to create evolutionary requirements that are necessary (2009, pp. 97-98). Traditional System Engineering (SE) includes controlled planning and a certain set of development steps that need to be followed. This ordered way of SE does not fit SoS well since Keating says that SoS emerge more than they are planned (2009, pp. 172, 188-189). Emergence is a major part of the setting and surprising events must be expected and natural.

When trying to oppose SoS to Systems of subsystems, some authors have identified five main tensions based on five characteristics of SoS. The tensions illustrate the differences between SoS and System of subsystems: autonomy, belonging, connectivity, diversity, and emergence. The characteristics are independent, decentralised, network-centric, heterogeneous and indeterminable where Systems of subsystems are conforming, centralised, platform-centric, homogeneous and foreseen. The degree of autonomy is high for SoS which are independent but the degree of autonomy is low for Systems of subsystems, which are conforming. The degree of belonging is low for SoS which are decentralized but belonging is high for Systems of subsystem which are centralised. Concerning SoS, connectivity is focused on network-centricity while Systems of subsystems are focused on platform-centricity. The diversity for SoS is high as they are heterogeneous but diversity is low for Systems of subsystem since they are homogeneous. The tension “emergence” describes the difference between SoS that are indeterminable while comparatively System of subsystem are foreseeable.

There are different views on how the characteristics of SoS differ from Systems of subsystems. This divergence opposes Saunders et al. (2005) shown in table 1 and Sauser et al. (2009)–as shown in table 2. Sauser et al. (2009) also describe the characteristics of Systems of subsystems and the tensions that are said to exist between the different characteristics.



*Paysage de mer au grand ciel,
Eugène Boudin (1860)*

System of Systems
Operational independence of components
Managerial independence of the components
Evolutionary development where the SoS changes over time to adapt to new circumstances
Emergent behaviour
Geographic distribution

*Characteristics of SoS
distinguished from Systems
of subsystems according to
Saunders. (2005, p.22)*

*Differences between SoS and
Systems of subsystems accor-
ding to Sauser et al. (2009)*

Tensions between the SoS and System of subsystems	System of Systems	System of subsystems
Autonomy	Independent	Conforming
Belonging	Decentralised	Centralised
Connectivity	Network-centric	Platform-centric
Diversity	Heterogeneous	Homogeneous
Emergence	Indeterminable	Foreseen

Each of these tensions can affect another one in an interdependency manner depending on the characteristics of a specific SoS. An example of what Sauser et al. (2009, pp. 205-207) means is that, for instance, a large amount of connectivity can cause a strong belonging, which can affect the way emergence will function. The

phenomenon of interdependency creates a challenge to the design of SoS. Sauser et al. (2009, pp. 212-214) also say that other challenges of importance for the future are management, measure capability, and framework for an entire process – technological as well as organisational – of designing SoS.

Controversies around Systems of Systems

There are different opinions about what constitutes a SoS and if it holds any real difference from normal Systems of subsystems. For example, Maier (1998) claims that Systems of Systems could simply be understood as more complex Systems of subsystems and the idea of continuum supports that argument. The issue about the differing features of complex systems and SoS are often about complex technology in the form of computer networks. It is a debated area and some examples of objections regarding SoS are: *“There is no nice line between Systems and SoS”*, *“There is no difference between SE for systems and SoS...”*, *“There is simply a need for better requirement management for SoS...”*, *“Thinking that traditional SE methods/techniques are sufficient for SoS is dangerous...”*, *“Standard SE applies but requires extensions”*, *“The only difference is no one is in control in a SoS...”*, *“Nothing is new. Any system that has subsystems is a SoS. We have been doing this forever”*, (Department of Defense, 2006, p. 9). It has been claimed, for instance, by Popper et al. (2004, pp. 6-7) and The Department of Defense (2006) that SoS is not a new field of research but rather an indication that engineering has lost its way in the sense that, possibly, problems have become more difficult and complex (2006). Instead of speaking of SoS, some authors like Holland (2006) prefer to use the notion of Complex Adaptive System (CAS), which can be used in understanding different complex systems like global trade, ecosystems, and controlling the internet with the help from computer-based models. Systems Engineering has not yet been developed into System of Systems Engineering (SoSE) to fully manage SoS. Jamshidi (2009, pp. 2-3) argues that System of Systems Engineering is a fairly young discipline on a high conceptual level viewing subsystems as parts of larger systems. The differences between SoSE and traditional SE are several according to Sauser (2006). System of Systems Engineering is focused on integrating numerous independent complex systems whereby traditional SE deals with single complex systems. System of Systems Engineering needs to adapt and manage SoS constantly, in a timely and holistic manner. Wilber (2009) says that SoSE needs the ability to adapt a SoS at shorter notice compared to SE, which is mainly unchanged with a focus on a single system resulting in an end product.

Discussion and conclusion

What is called SoS are complex interacting systems, taking into consideration that during the 1990s the amount of complex technology increased and SoS often consist of complex networked technologies that are interconnected to a greater degree than before the 1990s. Then, if complex technology, aiming at connecting an already complex system into a network, is also involved, the complexity increases even more. Problems appear to occur due to ambitious technology developments which mostly mean computerised communication systems. Going back to the example of the 787 as an air traffic system, we can look at it from both perspectives. We can consider it a very complex System of subsystems, its complexity lying in the communication network developed inside the plane and between the plane and the ground facilities, but remaining platform-centric. We can also consider that, when such a sophisticated

network system is developed between geographically dispersed subsystems, the nature of the system changes, the system becomes a network-centric System of Systems.

A System of Systems either stands for something new, a tool to engage in, for instance complex defence acquisition, or it constitutes a relabeling of, for instance, big and complex Systems of subsystems, which already exist as a concept. If the argument that SoS could be perceived in a continuum with different degrees of sophistication is true, the main question is whether SoS really is something new or a continuation of, for instance, a complex System of subsystems. The failures that SoS have experienced in the recent past, such as the Future Combat Systems developed for the U.S. Army and abandoned after years of developments and cost overruns, can be interpreted in two ways: either SoS are something new and we have not discovered ways to manage their development, or SoS are simply systems too large to be developed efficiently as one cohesive project. In both cases, the choice to engage in the development of SoS should be done prudently and great care should be taken since the alternative could entail very large risks ■

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