A Refined Terminology on System-of-Systems Substructure and Constituent System States

Jakob Axelsson
Mälardalen University and RISE Research Institutes of Sweden
Västerås, Sweden
jakob.axelsson@mdh.se

***Abstract*—In the field of systems-of-systems (SoS) engineering, there is broad agreement on a few characterizations, and these are currently being standardized. However, many aspects in the field still lack an established terminology. In particular, there are unclarities related to the internal structure of an SoS, and on the internal states of constituent systems. In this paper, a refined terminology is therefore proposed, which covers the internal substructure of an SoS; the states of constituent systems in relation to those substructures; and how it relates to hierarchical levels. This terminology can also be used to classify the characteristics of an SoS through different metrics. The terminology is illustrated through three examples of SoS applications in various domains.**

Keywords—system-of-systems, hierarchy, emergence, metrics, constellation, capability.

I. Introduction

Over the last few decades, considerable research has been conducted on systems-of-systems (SoS) and on SoS engineering (SoSE) [1]. This has led to a development of certain characterizations of SoS, and there is nowadays a broad agreement that Maier's five characteristics [2] is a useful way of describing what an SoS is. Standardization is ongoing to even further establish the taxonomy of terms used for describing SoS, and this includes also the Maier-Dahmann archetypes for SoS [2][3].

Despite this maturation of the field, we believe that the community is still far from a deeper understanding of all the aspects involved in SoSE. To reach further, the terminology of the field needs to be further evolved and refined, to find a richer and more precise way of articulating the problems at hand. The purpose of this paper is to suggest such a refinement that will allow researchers and practitioners to more precisely express the inner structure of an SoS, and how this relates to different states within the constituent systems.

The need for this terminology enhancement has become apparent for us in the study of several different SoS applications in areas such as truck platooning [4], road construction [5], urban mobility [6], and emergency response. In those applications, we have studied issues related to how constituent systems (CSs) make their independent decisions, and realized that many of the decision types were related to different states of the CS. We also found that across these diverse applications, the states and structural elements were recurring, and it would thus make sense to provide generic names to them.

The usefulness of this is obviously to allow SoS engineers to more easily communicate around the design problem in a specific case. However, even more so, it provides a value in comparing different SoS applications, since their characteristics can become clearer and provide better empirical data to improve our understanding of the nature of SoS. With that as a basis, better theoretical models can be developed, and be used to derive more stringent analytical techniques and new design guidelines leading to improved SoS being put into operation.

The remainder of this paper is structured as follows. In the next section, some related work will be discussed, with the purpose of providing a frame of reference. This is used to explain some of the current gaps in terminology. In Section III, the proposed extended terminology is introduced, and in Section IV it will be illustrated how this can be used to provide better characterizations of three example applications. In the final section, the conclusions are summarized, and some indications of future work is given.

II. Related Work

As mentioned in the introduction, Maier's characteristics [2] are widely accepted as a good description of an SoS. It consists of the following aspects:

1. *Operational independence* of the elements, meaning that the SoS is composed of systems which are independent and useful in their own right.
2. *Managerial independence* of the elements, in the sense that the CSs are separately acquired and integrated but maintain a continuing operational existence independent of the system-of-systems.
3. *Evolutionary development*, whereby SoS functions and purposes are added, removed, and modified with experience.
4. *Emergent behavior*, where the SoS performs functions and carries out purposes that do not reside in any CSs. The principal purposes of the SoS are fulfilled by these emergent behaviors.
5. *Geographic distribution*, indicating that the geographic extent of the CSs is large, and they can readily exchange only information and not substantial quantities of mass or energy.

The main problem with this characterization is that it leaves much room for interpretation. As an example, a small group of systems that carry out a limited task within a larger framework has these properties, but the overall framework does as well. So they are both SoS's, with one being contained within the other, and there are interactions between these levels. This obviously creates some confusion in dealing with real applications and it is one of the issues we aim to resolve with this paper.

Another commonly used characterization is that of Boardman and Sauser [7], which contains the dimensions of autonomy, belonging, connectivity, diversity, and emergence. Clearly, these are important aspects of an SoS, but their definitions also leave room for interpretation.

Maier [2] also provided a description of three different kinds of archetypes for SoS, based on the amount of central

This research has been partly funded by Vinnova, Sweden's Innovation Agency (grants no. 2016-04232 and 2018-00671).

control present. To this, Dahmann and Baldwin [3] provided an intermediate type, and this combined set contains the following four archetypes:

1. *Directed SoS* are integrated and centrally managed to fulfil specific purposes, and the CSs are subordinated when operating as part of the SoS.
2. *Acknowledged SoS* also have recognized objectives and a central manager, but the CSs retain independent ownership and objectives while operating within the SoS.
3. *Collaborative SoS* where the CSs voluntarily agree upon the purposes, without the coercive power of a central coordinator.
4. *Virtual SoS* lack centrally agreed purposes and have no central authority but rely on invisible mechanisms to produce emergent behavior.

Although these archetypes seem intuitive and relevant, a problem is that it is difficult when facing a concrete example of an SoS to say for sure of which archetype it is. This has triggered various attempts to better explain or interpret these archetypes, e.g. [8], but the vagueness and subjectivity remains despite these efforts. Obviously, it would be desirable to have objective ways of determining the archetypes, and some researchers have investigated alternative ways of characterizing SoS [9]. By providing a clearer terminology, our paper as a side-effect contributes some measures that can be used for an alternative characterization.

According to the draft ISO standard on SoS taxonomies, SoSE is "the process of planning, analyzing, organizing, developing, and integrating the capabilities of a mix of existing and new systems, including inter-system infrastructure, facilities and overarching processes into a system-of-systems capability that is greater than the sum of the capabilities of the constituent parts" [10]. The SoS capabilities are thus central, but it is unclear how the provisioning of such operational capabilities is actually carried out, and how the recombining of CSs to shift to another capability occurs. This is also addressed by the refined concepts proposed in this paper.

III. Proposed Terminology

We will now introduce the proposed refinement of the terminology around SoS, and as a first step some aspects of the substructure of an SoS will be introduced. Then, it will be shown how this substructure maps to different states of the CSs, that can be used to understand the decisions made by each independent part. The third part of the terminology shows how a hierarchical structure can also be linked to the previous concepts. Finally, it will be shown how this characterization naturally lends itself to providing metrics that can be used for an objective classification of an SoS.

A. SoS Substructure

An SoS is composed of a set of parts that are independent systems. Therefore, the characterization starts with a set of all systems that are in some sense relevant, and then a sequence of more delimited but useful subsets are identified:

- *Relevant system.* This is the set of systems that have capabilities that could be useful in the SoS.

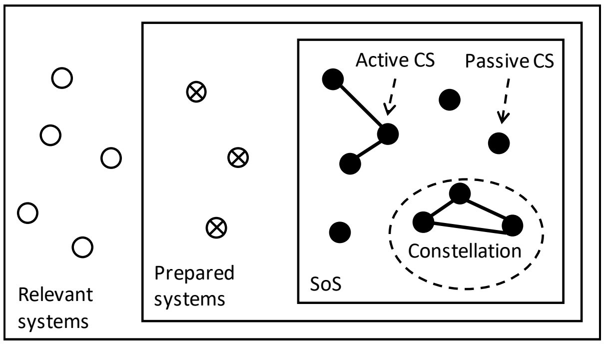

Fig. 1. SoS substructure.

- *Prepared system.* A prepared system is a relevant system that meets all the requirements the SoS poses on its constituents. This could for instance mean that the system has been modified to incorporate certain equipment or software needed to communicate with other constituents. This modification to become a CS can be seen as a "delta", or difference, to the original system, as discussed in [11].
- *Constituent system.* A constituent system is a prepared system that has actually joined the SoS. This could for instance mean that an information exchange has occurred telling other CSs about the existence of this CS; it could involve exchange of authentication and encryption keys; and it could include the establishment of contractual and financial agreements.
- *Constellation.* The fact that a system becomes a CS only means that it is now part of the family, but it does not necessarily interact with other CSs. To do so, it must create links to other CSs, allowing them to exchange information. A subset of CSs that have formed such links is called a constellation, and the constellation has a very important role as the provider of an SoS capability.

Note that all these terms should really be appended with "... with respect to a certain SoS." However, in many practical situations it is obvious which SoS is being discussed, and the abbreviated forms can then be used. It is only when two different SoS's are discussed simultaneously that the distinction must be made.

Based on the idea of constellations, two kinds of constituents can be distinguished (at a given moment in time):

- *Active CS.* A CS that is part of a constellation. It is only an active CS that works towards the SoS goals and needs to find suitable trade-offs against its own goals.
- *Passive CS.* A CS which is part of the SoS but not currently involved is a passive CS. It can safely prioritize its own goals and does not have a specific role in fulfilling SoS objectives.

These concepts are illustrated in Figure 1.

B. Constituent System States

Based on these sets, a number of states and transitions naturally emerge within a system that is relevant to the SoS. Those states are:

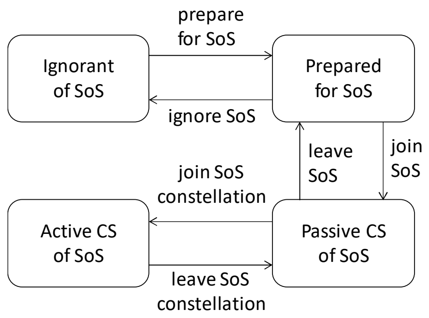

Fig. 2. Constituent system states.

- *Ignorant:* A system which has the relevant capabilities but does not meet the requirements of the SoS and is hence unable to participate.
- *Prepared:* A system which meets the requirements of the SoS but has not yet become part of it.
- *Passive:* A CS that has joined the SoS but is not participating in any constellation.
- *Active:* A CS that is participating in a constellation of the SoS.

Again, these are abbreviated states, and the full state names clarify which SoS it relates to. For the active state, it is sometimes also necessary to make it explicit which constellation it is a part of.

It is totally feasible to have a system that is a CS of several SoS at the same time. If the CS is capable of contributing to several SoS capabilities at the same time, it could also be part of several constellations simultaneously.

The states and transitions are illustrated in Figure 2. The exact nature of what it means for a CS to transition between two states is application specific, but some possibilities include:

- *Prepare for SoS*: To meet the SoS requirements, a system may need additional material resources, such as communication equipment, to be able to exchange information with other CSs. Additional software is also commonly needed, to implement the functionality required for the SoS collaboration. These updates to the system require investments in development and equipment.
- *Ignore SoS*: When the SoS evolves, there could be new requirements on the CSs, and in some cases it is not possible to meet those, causing the CS to return to the ignorant state.
- *Join SoS*: To become a constituent, the other CSs need to become aware of this new system, to be able to address it, and this also includes necessary security precautions, such as authentication and encryption. There could be contractual and monetary arrangements as part of this transition, to clarify what obligations the CS and SoS have towards each other. In some cases, in particular in directed or acknowledged SoS, there could be a compensation paid to the CS for its services to the SoS, and in other situations, such as collaborative or virtual SoS, there could be a fee that the CS has to pay for the benefits it gets by participating.
- *Leave SoS*: A CS may at some point find that it no longer wishes to collaborate in the SoS, e.g. because the cost-benefit relation is no longer favorable. However, it can also be that a CS is no longer desired by the others, in which case it is forced to leave. This could be achieved by revoking its credentials.
- *Join constellation*: In order to deliver a capability of the SoS, constellations are formed, and this means creating direct links between the involved CSs. Within the constellation, there is typically a continuous exchange of data from each CS to the others. When joining, there could also be contractual arrangements to sort out obligations or payments for creating incentives to join.
- *Leave constellation*: When the constellation is no longer meaningful, or possible to uphold, a CS leaves it and returns to its passive state.

One should note that it is the CS itself (or its owners) that decide when to transition between the states. Understanding the nature of those decisions is a key in the design of an SoS in order to create emergent behavior. The available mechanism on the SoS level for influencing these transitions within a CS is to modify the incentives for the associated decisions, i.e. changing the cost-benefit relation for the CS.

There are also different lifecycle-related organizational roles involved in these transition decisions:

- *Developing organization*: Decides on the prepare for/ignore SoS transitions.
- *Acquiring/owning organization*: Decides on the join/leave SoS transitions.
- *Operating organization*: Decides on the join/leave constellation transitions.

The first two are related to the managerial independence of the CS, whereas the final one relates to its operational independence.

C. Hierarchical Levels

The analysis of SoS dynamics can be at different hierarchical levels that correspond to the SoS substructures. We propose the following names to distinguish between the levels of analysis:

- *Macro analysis:* The scope is the SoS as a whole in its context, and the analysis can answer questions about the overall emergent properties on an aggregated level. Typical issues involve the need for preparation of a CS, and the attractiveness of the SoS for CSs, i.e., how likely they are to join. It can also deal with the overall evolution of the SoS and evaluate the effects of alternative ways of setting up the mechanisms of the SoS.
- *Meso analysis:* The scope is the internal dynamics of the SoS, dealing with how constellations form and dissolve, and the effects this will have on the emergent properties.
- *Micro analysis:* The scope is the internal operations of a steady-state constellation, i.e. one where the

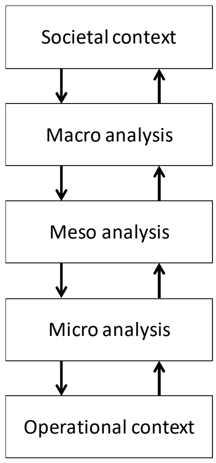

Fig. 3. Hierarchical levels.

active participants are fixed. The analysis thus focuses on what capability and performance the interactions between the CSs produces. This relates also to what trade-offs the CSs make between the SoS goals and their own private goals.

The hierarchical levels are illustrated in Figure 3. As is always the case in hierarchical systems, there is a difference in temporal and spatial resolution between the levels. The higher up, the longer time between interesting events, and also the larger the geographical distribution of entities.

The analysis on each level must consider the level above and below. For instance, the meso level needs to take into account constraints and directives coming from the macro level, and also incorporate assumptions about the properties emerging at the micro level. This is commonly done by creating simplified models of the adjacent levels, that can serve as a context for the level of interest, which is modeled in more detail. For the micro analysis, the level below is the operational context, which typically includes elements of the physical reality. For the macro analysis, the level above is the societal context, which provides constraints such as laws and regulations.

D. A Foundation for Characterizing SoS

The substructures of the SoS described above also give a foundation for a new characterization that could be more objective and nuanced than the Maier-Dahmann archetypes currently in common use. The foundation would be a number of metrics, which to some extent relate to the Boardman-Sauser characteristics [7], such as:

- *Activity*: What proportion of the CSs are active, i.e. part of a constellation, on average?
- *Connectivity*: What is the average size of a constellation, in absolute numbers or in relation to the size of the SoS?
- *Dynamicity*: What is the average life-time of a stable constellation?
- *Evolution rate*: What is the average time a system remains a CS, in absolute numbers or in relation to the life-time of the SoS?
- *Distribution*: What is the geographical distribution of a constellation, in absolute numbers or in relation to the geographical distribution of the SoS?
- *Diversity*: How many different types of CSs exist? In this case, two CSs are of different types if one of them has a capability of relevance to the SoS that is not present in the other CS.

Some of these metrics are similar to those provided by Cook and Pratt [9], but with the ambition of making them more measurable and less subjective. The diversity (or system types) and connectivity dimensions were also proposed by DeLaurentis and Crossley [12].

The metrics make it easier to compare one SoS to another and look for differences and similarities. In this way, classes of similar SoS could be found and be a basis for refined design guidelines. For an operational SoS, they could be measured quantitatively, and in a development phase a qualitative approach is possible.

IV. Illustrative Examples

In this section, the usage of the proposed terminology will be illustrated through three examples of SoS applications. The purpose of this is to give a bit more insight into the power of the terminology in real cases. It also shows that the metrics vary widely in range between applications, which is an indication that they have some expressive and discriminant power. A qualitative assessment of these applications using the metrics of Section III.D is summarized in Table I.

A. Truck Platooning

The idea of platooning is that a lead vehicle, which is driven manually, is followed closely by several other vehicles using automated driving. The benefit is that aerodynamic drag can be substantially reduced by shortening the distance between the trucks, leading to lower energy consumption. However, there is also a cost in that trucks must wait for each other to form platoons, which can increase transportation time and lower the usage ratio of trucks.

CS states and transitions. To prepare a truck for platooning, it needs to be equipped with short-range radio communication with other trucks to control the speed, and thus the distance between them. It also needs additional sensors to enhance safety. To join the SoS, it needs access to off-board mediating systems that can hand out the authentication and encryption keys, and connect to mediating services that make it easier for trucks to find each other and form constellations (the actual platoons) [13].

Hierarchical levels. A macro analysis of this SoS deals with the overall rate of platooning that occurs in the SoS, depending on its design. The meso analysis will look at a single platoon, and see how it is formed and dissolved, and how this interacts with elements in the traffic environment. The micro analysis, finally, investigates control algorithms for keeping distances within a platoon under different traffic conditions, and can be used to evaluate operational risks [11].

Metrics. The platooning SoS is relatively simple in the sense that it basically has one key capability (to reduce fuel), and a low diversity (all trucks have similar capabilities and are thus substitutable in a constellation). The ambition is that the CSs in the platooning SoS should be active as much as possible, to maximize overall fuel savings, but when traffic is

TABLE I. CHARACTERISTICS OF EXAMPLE SOS.

Dimension	Applications		
	Platooning	***Construction***	***Emergency***
Activity	Moderate	High	Low
Connectivity	Low	Moderate	Moderate
Dynamicity	Low	Moderate	Low
Evolution rate	Moderate	Moderate	Moderate
Distribution (constellation)	Low	Moderate	Moderate
Distribution (SoS)	Global	Regional	National
Diversity	Low	Moderate	High

sparse, the waiting times to form platoons could become too long, which limits activity.

The connectivity is low. A constellation will typically involve just a few trucks, and the distribution of a constellation is thus very small (a few hundred meters), in particular when compared to the distribution of the SoS which could cover many countries or even be global, since trucks often travel long distances.

The dynamicity is fairly high, and few constellations will survive more than a few hours, due to the typical transportation distances, but also to regulations that limit how many hours a driver can work without pausing. Once the platooning standards are deployed, it is expected that most trucks will be prepared and join the SoS. However, the average life-time of a truck is in the order of ten years or so, thus at least around 10% of the CSs will be exchanged every year.

B. Road Construction

In road construction, the capabilities of a number of working machines are combined to create an industrial process. The processes include the production of aggregate (i.e., crushed stones) in a quarry, transportation to a road site, building a road bed, asphalt production, etc. To build a specific road, these processes are combined in a project. Current efforts in SoS engineering aim at optimizing these processes through improved communication between the working machines and the production management system [5]. The constellations of this SoS are arranged in a poly-hierarchy, so that one CS in a constellation is also part of a higher-level constellation (process).

CS states and transitions. To prepare a system for this SoS, it needs similar equipment and software as in the platooning case, and this is also true for joining the SoS. However, the decision to join a constellation is based on a contractual agreement with the next level in the process poly-hierarchy and comes with a monetary compensation.

Hierarchical levels. A macro analysis of the construction SoS deals with the overall effects on productivity improvement that can be achieved. The meso analysis would look at how resources can be assembled into a constellation to deliver a new SoS capability, i.e., a new process. The micro analysis studies the performance of a stable, operational process in, e.g., a quarry or road site.

Metrics. The road construction SoS contains a number of capabilities, corresponding to the subprocesses, and there is a large diversity in different kinds of machines used. The connectivity within a subprocess is moderate, ranging from a few to a few tens of machines.

The dynamicity varies depending on the capability provided by the constellation. An aggregate production constellation can be stable for weeks or months, whereas an asphalt laying constellation could be active for a few days, and some other constellation for even shorter periods of time. The evolution rate is similar to the truck platooning case, with new CSs being added based on the life-time of machines.

The geographical distribution of a constellation is moderate, typically up to a few kilometers. The SoS would typically have a distribution corresponding to a national or regional level, since it is costly to move the machines over longer distances.

C. Emergency Response

Most societies have resources that can be called into action in the case of a crisis, such as natural disasters, terrorist attacks, or similar events. Often, these organizations combine public and private resources in an SoS [14], and a typical characteristic is that the events themselves are hard to predict. Therefore, the SoS needs to be designed so that its limited resources can be combined in a large number of ways to deal with a wide range of scenarios. This tends to lead to a high diversity among the CSs.

CS states and transitions. In this SoS as in the previous examples, the preparation is to meet certain technical standards to allow communication. This can either be mandated through regulations, when it comes to public procurements, or as a prerequisite for private resources to join the SoS. For this joining to occur, most likely the public authorities need to compensate private actors for the preparation, and some agreement on a stand-by fee. When the crisis forms, the different resources will be called into action to form constellations that provide the most adequate response to the situation at hand, and this engagement requires further compensation to the CS owners.

Hierarchical levels. A macro analysis of the emergency response SoS includes investigating what range of capabilities and their combinations that the SoS can produce to meet varying scenarios. On the meso level, a given scenario is in focus and the analysis can study how a constellation is formed to deliver the required capability. Finally, the micro analysis shows how the CSs collaborate in the provisioning of that capability.

Metrics. The emergency response SoS is characterized by a fairly low activity, where in many cases CSs are used for other purposes when not responding to a crisis. Once a constellation is formed, it is of moderate size in comparison to the overall SoS size, since a specific situation requires only some of the capabilities and hence only some of the resources of the SoS.

The constellations are short-lived, and could range from a few hours to a few weeks, to deal with the immediate emergency. The evolution rate is moderate between emergencies, and mainly consist of replacing old equipment, but also of evolving the capability of the SoS based on new scenarios, which could require new types of systems. However, during a crisis, there could also be a need to very rapidly evolve the SoS to enhance capabilities, and thereby add new CSs that were not foreseen to be needed.

The geographical distribution of the SoS is typically national or regional and follows the geographic organization of government. A constellation can vary in size, but many crises occur in a limited geographical region which could be a small part of a city (in case of a terrorist attack), up to a region (for some natural disasters).

V. Conclusions

In any area of research, expressiveness, clarity, and precision in the language used to discuss the problems is a prerequisite to success. Despite the fact that there is an ongoing standardization of the taxonomy on SoSE, we believe that there is still a lot to be done in improving the terminology used in the field. Based on our work in a series of SoS applications, a number of generic concepts have emerged, where we think that a refinement of terminology is necessary, and the contribution of this paper is to propose such a set of terms. The proposal includes a description of certain common substructures of the SoS, and the corresponding states within a CS. It also identifies different levels of analysis, that are relevant for an SoS, and uses the terminology to define a set of metrics that can be used to characterize an SoS. Finally, the concepts introduced are applied in three examples of different nature, providing an initial validation of their usefulness.

Although the provided terminology is hopefully a step in the right direction when it comes to improving how SoS can be analyzed, it requires further validation to ensure that it is generic enough to become part of future updates to the SoS taxonomy standards. Also, there are certainly many other aspects of SoSE that could benefit from improvements in the taxonomies, beyond both the proposed standards and the aspects covered in this paper.

References

[1] J. Axelsson, "A Systematic Mapping of the Research Literature on System-of-Systems Engineering," in *IEEE 10th Annual System of Systems Engineering Conference*, 2015.

[2] M. W. Maier, "Architecting Principles for Systems-of-Systems," INCOSE Int. Symp., vol. 6, no. 1, pp. 565–573, Jul. 1996.

[3] J. S. Dahmann and K. J. Baldwin, "Understanding the Current State of US Defense Systems of Systems and the Implications for Systems Engineering," in 2008 2nd Annual IEEE Systems Conference, 2008, pp. 1–7.

[4] J. Axelsson, "An initial analysis of operational emergent properties in a platooning system-of-systems," in 12th Annual IEEE International Systems Conference, SysCon 2018 - Proceedings, 2018, pp. 1–8.

[5] J. Axelsson, J. Froberg, and P. Eriksson, "Towards a System-of-Systems for Improved Road Construction Efficiency Using Lean and Industry 4.0," in 13th Annual Conf. on System of Systems Eng., 2018, pp. 576–582.

[6] J. Axelsson and S. Nylander, "An Analysis of Systems-of-Systems Opportunities and Challenges Related to Mobility in Smart Cities," in 13th Annual Conf. on System of Systems Eng., 2018, pp. 132–137.

[7] J. Boardman and B. Sauser, "System of Systems - the meaning of of," in 2006 IEEE/SMC International Conference on System of Systems Engineering, 2006, pp. 118–123.

[8] J. A. Lane and D. J. Epstein, "What is a System of Systems and Why Should I Care?," 2013.

[9] S. C. Cook and J. M. Pratt, "Typology dimensions for classifying SoSE problem spaces," in 11th System of Systems Engineering Conference, 2016, pp. 1–6.

[10] ISO/IEC/IEEE, "Draft standard 21841 Systems and software engineering - Taxonomies of systems-of-systems," 2018.

[11] J. Axelsson and A. Kobetski, "Towards a risk analysis method for systems-of-systems based on systems thinking," in IEEE International Systems Conference (SysCon), 2018, pp. 1–8.

[12] D. A. DeLaurentis and W. A. Crossley, "A Taxonomy-based Perspective for Systems of Systems Design Methods," in *2005 IEEE International Conference on Systems, Man and Cybernetics*, vol. 1, pp. 86–91.

[13] J. Axelsson. "Business Models and Roles for Mediating Services in a Truck Platooning System-of-Systems," in 14th Annual Conf. on Systems of Systems Eng., 2019.

[14] L. John, G. B. John, M. Parker, B. J. Sauser, and J. P. Wade, "Self-organizing cooperative dynamics in government extended enterprises," IEEE Syst. J., vol. 12, no. 3, pp. 2905–2916, 2018.