Systems-of-systems for border-crossing innovation in the digitized society

A strategic research and innovation agenda for Sweden

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Denna agenda är framtagen inom ramen för Strategiska innovationsområden, en gemensam satsning mellan VINNOVA, Energimyndigheten och Formas. Syftet med satsningen är att skapa förutsättningar för Sveriges internationella konkurrenskraft och hållbara lösningar på globala samhällsutmaningar.

Summary

This report constitutes a strategic research and innovation agenda for the area systems-of-systems. The agenda has been developed during the first half of 2015 in a project led by SICS Swedish ICT AB, in collaboration with INCOSE Sweden and a large number of representatives from industry and academia, with financial support from Vinnova. The overall conclusion of the agenda is:

Sweden needs a world-leading capability to rapidly develop trustworthy systems-of-systems

A system-of-systems (SoS) can informally be defined as a group of independent collaborating systems. The elements of an SoS, called constituent systems, retain an operational and managerial independence, but when combined in a certain way, they provide together a new capability that is emergent from their cooperation. There are many applications of SoS, often as a consequence of the digitization of society which opens new possibilities for system integration. Examples can be found within command and control systems for defense and civilian crisis management; construction and mining; manufacturing and the reindustrialization; transportation; and health care. System integration is traditionally a Swedish area of strength, and by improving SoS knowledge, competitive advantages can be reached. SoS is also an important enabler for innovation, through the ability to combine existing technical products, processes, and organizations in new ways. Having the ability for rapid SoS development is very important for businesses to bring new innovations to market. However, to advance the practice of SoS engineering, a number of challenges need to be addressed, including improving the theoretical foundations; the socio-technical aspects; architecture; modeling and simulation; interoperability; trust; business and legal aspects; development processes and methods; and standardization.

As part of the agenda project, a survey has been done of international and Swedish research in the area. Internationally, the SoS field is dominated by US researchers, with a very strong focus on military and space applications. A large number of people are involved, but few persons focus on the area. In comparison, Sweden has entered the research area much later, and only now is attention growing. As is the case internationally, few researchers focus on SoS, and many of them do not even call their research SoS. Activities are scattered over many organizations throughout the country. Many of the researchers in SoS in Sweden come from a background in Software Engineering or Control Engineering, and this is in contrast with the international research, which has its basis in Systems Engineering. In Sweden, research topics such as business aspects (in particular innovation), control systems, governance, and Internet of Things are more pronounced than internationally. However, there is little research in Sweden on the underlying, fundamental principles of SoS engineering. This is likely to be in part a consequence of the funding strategies currently implemented. The analysis shows a broad but scattered Swedish research community lacking critical mass. There is a high competence in software and control engineering, and in empirical research methods, but the lack of systems engineering competence is alarming, since it is fundamental for desired advances, such as in the reindustrialization (Industry 4.0).

To achieve the desired capability in SoS development requires knowledge, competence, and capacity, which are provided through substantially increased research and education actions. It is suggested that research in the area is organized as a national SoS center-of-centers that coordinates activities at different academic member organizations. This requires increased research funding. There is also an urgent need for education in systems engineering, systems thinking, and SoS. It is proposed that the center-of-centers also takes responsibility for this, by developing joint courses in those disciplines, including on-line courses for practitioners, and PhD schools for industrial and academic doctoral students. To complement this, societal actions are needed to remove obstacles for building SoS, and enforcing standards. Finally, it is necessary to create meeting places, including triple helix flagship projects, that can fuel the interactions between individuals and organizations interested in SoS.

Sammanfattning

Denna rapport utgör en strategisk forsknings- och innovationsagenda för området system-av-system. Agendan har tagits fram under första halvåret 2015 i ett projekt under ledning av SICS Swedish ICT AB, i samarbete med INCOSE Sverige och ett stort antal representanter för industri och akademi, med finansiellt stöd från Vinnova. Agendans övergripande slutsats är:

Sverige behöver en världsledande förmåga att snabbt utveckla förtroendeingivande system-av-system

Ett system-av-system (SoS) kan informellt definieras som en grupp av oberoende samverkande system. Elementen i ett SoS, som kallas ingående system, behåller ett operativt och ledningsmässigt oberoende, men när de kombineras på ett visst sätt så skapar de tillsammans en ny förmåga som framträder från deras samverkan. Det finns många tillämpningar för SoS, ofta som en följd av digitaliseringen av samhället som öppnar nya möjligheter för systemintegration. Exempel finns inom bland annat ledningssystem för försvaret och civil krishantering; anläggningsarbete och gruvor; tillverkning och nyindustrialisering; transport; samt hälsovård. Systemintegration är av hävd ett svenskt styrkeområde, och genom att öka kunskapen inom SoS kan konkurrensfördelar uppnås. SoS är också en viktig möjliggörare för innovation, genom förmågan att kombinera existerande tekniska produkter, processer och organisationer på nya sätt. Att kunna utveckla SoS snabbt är väldigt viktigt för att så kvickt som möjligt få ut nya innovationer på marknaden. Dock finns ett antal utmaningar som måste tas om hand för att förbättra kunskapen inom SoS-utveckling, och dessa innefattar de teoretiska grundvalarna; sociotekniska aspekter; arkitektur; modellering och simulering; interoperabilitet; förtroende; affärsaspekter och legala överväganden; utvecklingsprocesser och metoder; samt standardisering.

En del av agendaprojektet har varit att sammanställa den internationella och svenska forskningen inom området. Internationellt domineras SoS av amerikanska forskare, med ett mycket starkt fokus på militära tillämpningar och rymden. Ett stort antal personer är involverade, men få av dessa fokuserar på området. Som jämförelse har Sverige gett sig in sent på detta forskningsområde, och det är först nu som intresset ökar. Precis som internationellt är det få forskare här som fokuserar på SoS, och många av dem kallar inte ens sin forskning vid detta namn. Verksamheten är spridd över många organisationer i landet. Många SoS-forskare i Sverige kommer från en bakgrund inom mjukvaruutveckling eller reglerteknik, och detta skiljer sig från internationella forskare, som normalt härstammar från systems engineering. I Sverige betonas affärsaspekter (i synnerhet innovation), reglersystem, ledning, och sakernas Internet i högre grad än internationellt. Det finns dock lite forskning i Sverige kring de underliggande, fundamentala principerna för utveckling av SoS. Detta beror antagligen till del på de finansieringssätt som för närvarande finns att tillgå. Analysen målar upp en bild av ett brett, men spritt, svenskt forskarsamfund som saknar kritisk massa. Det finns hög kompetens inom mjukvara och reglerteknik, och inom empiriska forskningsmetoder, men avsaknaden av kompetens inom systems engineering är alarmerande, då den är avgörande för framsteg, t ex inom nyindustrialiseringen (Industri 4.0).

För att uppnå den önskade förmågan inom SoS-utveckling krävs kunskap, kompetens och kapacitet, vilket kan uppnås genom markant ökade insatser inom forskning och utbildning. Här föreslås att forskningen kraftsamlar i ett nationellt centrum-av-centra för SoS som koordinerar aktiviteterna inom de ingående akademiska organisationerna. Detta kräver ökad forskningsfinansiering. Det finns också ett skriande behov av utbildning inom systems engineering, systemtänkande, och SoS. Det föreslås därför att centret-av-centra även tar ansvar för detta, genom att utveckla gemensamma kurser inom dessa discipliner, inklusive nätbaserade utbildningar för verksamma ingenjörer, och doktorandskolor för både högskole- och industridoktorander. Som ett komplement krävs också åtgärder av samhället för att ta bort onödiga hinder för att utveckla SoS, och genomdriva standarder. Till slut behöver också mötesplatser skapas, inklusive trippelhelix-baserade flagskeppsprojekt, som kan ge bränsle åt interaktionen mellan individer och organisationer med ett intresse för SoS.

Acknowledgments

This report is the result of efforts by many people, more than can be named in a few paragraphs. I would like to thank the organizations who made the work possible in the first place, by supporting the application, namely Saab Aeronautics, FOI, Volvo Cars, Volvo Technology, Volvo Construction Equipment, Syntell, Decisionware, and INCOSE Sweden, and Vinnova who provided the funding.

The material is to a large extent the result of the intellectual contributions at a series of workshops, and I am grateful for the people who took the time to attend, and shared so much insight and experience that improved everyone's understanding of the nature of systems-of-systems. These individuals are listed in Section 6.1 of the report.

Important contributions were also made by a number of researchers, as well as employees of various universities, funding agencies, and research institutes, who took the time to respond to surveys and provide details about their research. These persons are listed in Section 6.2, and without their help, it would not have been possible to understand the status of Swedish research.

In writing the report, it has been impossible to accurately capture everyone's opinions, nor to make full use of the rich data collected. The report must therefore be seen as the interpretation of the author, and any error or omission is the result either of mistakes, or by choices that had to be made to keep the report within a reasonable length.

J.A.

Contents

1 Introduction

This report describes the results of a project to develop a strategic research and innovation agenda for the area systems-of-systems (SoS). The aim is to create an overall picture of effort needs to strengthen Sweden in this important area, which today is fragmented both in industry and academia. The project has been led by SICS Swedish ICT AB, and was carried out in collaboration with a number of industry partners from various sectors. The project has also been supported by the Swedish chapter of the International Council on Systems Engineering (INCOSE Sweden), which contributed with a broader network in the area.

1.1 Project background and objectives

The traditional way to develop complex systems involves a number of components which are assembled into a whole by adjusting the components so that they fit together. The results are tested and then delivered as a unit to the receiving client. In recent years, it has become more common to instead integrate existing systems with each other, so that they can work together for a common purpose. The result is a system-of-systems. This integration is often dominated by information technology solutions, but other technologies may be included.

Characteristic of an SoS compared to a traditional integrated system is that each constituent systems in the SoS has a value in itself and can be used outside the SoS, while the components of the integrated system has limited value outside of its context. This also means that systems integration changes character from being an internal activity of a system development organization, to become a dynamic activity that involves several different organizations, each of which owns or is responsible for some components.

The development of SoS was noticed early in the defense sector, where needs are often found to integrate different systems. For example, the implementation of a specific operation requiring airplanes and ships to interact, and be integrated through information exchange. These needs have led to the development of military standards and guidelines for SoS (DoD, 2006). However, these are usually on a rather abstract level, and often focused on just the defense sector's needs and special circumstances. In the IT sector, it is now a routine to do service integration using so-called service-oriented architecture (SOA), but this is often lacking connections to physical products and the requirements they impose. The integration is also primarily within an organization, while SoS are characterized by different constituent systems being owned by different organizations. Applications of SoS in other sectors is still in its infancy, but the area's importance is highlighted especially in the European Union's Digital Agenda[1].

The purpose of this project was to create a breeding ground for successful and high-quality development of SoS in Sweden, and identify actions required to achieve it. The aim was to make a map of the present situation and the needs of industry, society and research, as well as clarifying the potential for cross-border innovation by SoS. The concrete goal was to compile these results in an agenda documents, which is achieved through this report.

An important and intentional side effect of the project was also to form an expert network in the area of SoS, by creating meeting places where practitioners and researchers from different sectors could meet and learn from each other.

[1] http://ec.europa.eu/digital-agenda/en/system-systems

1.2 Project overview

The project was formally approved in late November 2014, and started a few weeks later. The end date of the project was June 30, 2015, giving approximately 6 months duration. The project was funded by Vinnova, the Swedish government agency for innovation systems, with a budget of 400 000 SEK.

The project consisted of three parts, namely an actor perspective, a research perspective, and a synthesis, and the resources were roughly split equally over these parts, giving approximately three working weeks to each of them. The parts are described in more detail in the following subsections.

1.2.1 Actor perspectives

The aim of this activity was to collect and analyze the current situation, and identify challenges and common issues from industry and the public sector. It was implemented as a series of three full-day workshops, taking place on February 6, March 13, and April 22, 2015. Parts of the workshops were used for focus group-like studies, where participants worked in groups on the issues.

The first workshop focused on characterizing the SoS area, and was to a large extent driven by short presentations from the participating industry, where they described their view of SoS and provided concrete examples. One of the issues that repeatedly came up was the lifecycle of the SoS, and the second event therefore focused on this, and also on how existing systems engineering standards can be applied to SoS. In the third workshop, the group worked hands-on with a couple of SoS examples, to get a deeper and richer understanding of issues. At the meeting, the preliminary contents of the agenda was also discussed, as input to the synthesis activity.

In the workshops, a wide range of perspectives were included due to the breadth of the participants' backgrounds. In order to converge on a common understanding of the area, considerable time was spent on discussing general characteristics and definitions. This was very valuable, since it made differences between various domains explicit, and also increased the knowledge of everyone participating. In order to maintain this knowledge for the future, Chapter 2 of this report has been dedicated to a description of the SoS area, based on the discussions and also on key references in the literature. Other parts of the results from the workshops are captured in Chapter 4, which describes the actual agenda.

1.2.2 Research perspectives

The purpose of the second activity was to establish the current state of research internationally and in Sweden. The first part was done mainly through a systematic mapping of the research literature, which was carried out in late December 2014 and January 2015. The study included over 3,000 research papers, and focused on establishing data about the research community, what research topics are being studied, and what application areas are addressed. This was complemented with participation in the leading conference in the area, the IEEE System of Systems Conference, which was held in San Antonio, Texas, in May 2015. At this conference, the literature mapping was also presented to the international research community, which can be seen as a validation of the results.

To capture the state of Swedish research, an extensive survey was performed, in which all relevant funding agencies, universities and research institutes were contacted and asked to report their activities in the area. This led to the identification of a large number of researchers, who were asked to report more details on what specific topics they study. The survey was initiated in December 2014, and most of the data had been gathered by March 2015. As a follow up to the survey, it was decided to organize a research oriented workshop to complement the industry oriented ones described in the previous subsection. This workshop, which was entitled the 1st Scandinavian Workshop on the Engineering of Systems-of-Systems (SWESoS) and took place May 27, 2015, was slightly more formal, asking prospective participants to send in extended abstracts, which were collected in a proceedings volume (Axelsson, 2015b).

The results of this part are described in more detail mainly in Chapter 3 of this report, with Section 3.1 focusing on the international perspective, and Section 3.2 on the Swedish.

1.2.3 Synthesis

In the third activity, the results of actor and research perspectives were compiled and compared. Based on this, a number of measures are identified which would strengthen SoS in Sweden. The project did not make any a priori limitations on the types of strategic initiatives to consider, but intended to create a broad picture of needs. The activity included the writing of this report, and also the creation of presentation material, which will be used after the formal ending of the project to communicate the results both in writing and orally to interested parties.

The identified actions are described in more detail mainly in Chapter 4 of this report.

1.3 Participants

The initial project application was supported by the following organizations:

- SICS (project leader)
- Saab Aeronautics
- FOI
- Volvo Cars
- Volvo Technology
- Volvo Construction Equipment
- Syntell
- Decisionware
- INCOSE Sweden

All these organizations have participated in the work, but the intention has all along been to make the project open to other interested parties, and a large number of other organizations have been reached, mainly among the members of INCOSE Sweden. In the academic sector, many researchers have also participated by providing data about their research and by taking part in the academic workshop.

The persons who have actively participated in the project are listed in Section 6.

1.4 Guidance to the reader

The ambition when writing this report has been to give a full and detailed account of how the project was carried out and of its results. However, the drawback of this approach is that the text becomes too detailed for many readers. Therefore, the document has been structured so that it can be read in parts, and we will now try to give the reader some guidance to that structure:

- **Chapter 2** provides an overview of the SoS area, introducing key terminology and challenges. If you are already acquainted with the area, or has a relevant intuitive understanding of it, you may skip this chapter.
- **Chapter 3** gives an account of the research frontier, internationally and in Sweden. If you are not interested in the research perspective, you may skip this chapter entirely.
- **Chapter 4** presents the actual research and innovation agenda, and this should probably be read by everyone. However, if you are already convinced about the importance of the area, you may skip Section 4.1.

Each chapter starts with a summary, and if you are only interested in an overview of the results of the chapter, you can just read this part.

2 Systems-of-systems principles and applications

Chapter summary. *Systems-of-systems (SoS) have their roots in the disciplines of systems thinking and systems engineering, but an SoS has a distinguishing set of properties that makes it necessary to define particular techniques for dealing efficiently with their development. The key properties are that the elements, called constituent systems, of an SoS retain an operational and managerial independence. The focus when building the SoS is then to compose the constituent systems in such a way that they together create the desired emergent behavior, and continue to do so as the system and its elements evolve. Depending on how loosely integrated the constituent systems are, and what authority the SoS level can exercise over them, different archetypes can be identified. In the development of an SoS, particular emphasis has to be placed on the life-cycle aspects, ownership of the SoS, the value it creates, and how to ensure the emergent properties are the desired once. There are many applications of SoS, often as a consequence of the digitization of society which opens new possibilities for system integration. Examples can be found within command and control systems for defense and civilian crisis management; construction and mining; manufacturing; transportation; and health care. In these areas, SoS give the possibility to rapidly recombine existing systems to form new innovations that can improve efficiency of a process, or reduce costs, and thus both bring a competitive advantage and increase customer and societal value. To advance the practice of SoS engineering, a number of challenges need to be addressed, including improving the theoretical foundations; the socio-technical aspects; architecture; modeling and simulation; interoperability; trust establishment; business and legal aspects; development processes and methods; and standardization. There are also a number of other disciplines, with which there would be a mutual benefit to increase interaction with the SoS area. These include cyber-physical systems; Internet of things; software ecosystems; and enterprise architecture.*

In this chapter, we will describe the SoS area in a bit more detail. The material presented here is based on studies of the research literature, combined with three workshops with practitioners in Sweden during the spring of 2015. Those workshops were mostly run using a focus group like method, as described in Section 1.2.1 above. The chapter is structured as follows: In the first section, some fundamental concepts from systems thinking and systems engineering are introduced. Then, the key characteristics of SoS are discussed, together with the consequences this leads to, followed by a set of key questions to ask in the development of an SoS. In Section 2.4, some application areas are introduced, followed by an identification of key challenges. In Section 2.6, finally, some related areas are described.

2.1 Foundation from systems thinking and systems engineering

SoS engineering is about building complex systems, and much of what we know in this field has been developed within the discipline called Systems Engineering (SE), which in turn has its theoretical basis in work which is often collectively referred to as "systems thinking". This encompasses key elements from disciplines such as cybernetics, general systems theory, operations research, etc. (Ingelstam, 2012). In this section, a brief account of these foundations will be given, as a support for explaining SoS in the following sections.

In systems thinking, a key relation is between the *system* (the whole) and its *elements* or parts, where the elements are interacting with each other. By composing the elements in a certain way, properties and behavior is created which cannot be attributed to any of the individual elements in isolation, and must hence be regarded as properties and behavior of the system. This is referred to as *emergent* properties and behavior. The fundamental idea in systems thinking is that the system cannot be analyzed by looking just at the individual elements, but must be seen as a whole, to capture this emergence. The interactions between the elements are important in this, and especially different kinds of *feedback loops*, both negative (stabilizing) and positive (amplifying) feedback. Understanding these interactions is central when designing a system to achieve a certain desired emergent behavior, and avoid undesired behavior and properties (Ackoff, 1971).

What constitutes a system is not given by nature, but is a concept in the eye of the beholder. Depending on your interest, you may choose to view one set of elements as a system, whereas another person, with other objectives and interests, finds it more meaningful to view a different set of elements as the system. The relation between the system and its elements is recursive, so an element of one system may be viewed as a system in itself, with its own elements, thereby creating a *hierarchy*. To clarify what “the system” is in a given context, the term *system-of-interest* is used to denote the top-most level that is focused in a certain situation by a certain individual or organization (ISO, 2008). By defining the system-of-interest, it is also clarified what the border is between the system and its environment, which is critical to efficiently deal with the design of the system. Often, a useful heuristic for identifying the system-of-interest is to consider what the person or organization can influence (the system) and what it has to adapt to (the environment).

A distinction is sometimes made between *hard systems* and *soft systems*, where hard systems are typically dominated by technical questions, and soft systems have a focus on humans and organizational aspects (Checkland, 1993). The latter typically uses methods which are less quantitative, and requires understanding the individuals’ motivations and viewpoints.

SE is a practically oriented discipline which applies the foundations from systems thinking to concrete engineering problems, focusing on processes and methods for successfully building complex systems involving large development organizations. It is an interdisciplinary approach, which focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal. SE considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs (INCOSE, 2011).

In SE, the emphasis is on developing a certain system-of-interest, but it is also acknowledged that certain surrounding systems must be included in the analysis as well, which support different aspects of the system’s lifecycle, such as development, production, operation, or maintenance. Such supporting systems are called *enabling systems*. Even in cases where the system-of-interest is primarily technical, the enabling systems are often at least partly organizational, which makes also the soft systems approach a natural part of SE.

2.2 Key characteristics of SoS

It is a quite common misunderstanding that the term SoS refers to large and complex systems in general, and it is therefore important to sort out what is meant by an SoS. As the term implies, the system-of-systems is a system in the sense used in systems thinking and SE, and therefore the principles described in the previous section apply to the SoS as well. However, not every system is an SoS, meaning that there are additional characteristics that an SoS has, which are not common in other systems. That is, the set of SoS’s is a subset of the set of all systems.

Any subset of the set of all systems has its own characteristics, which give rise to new methods and techniques. For instance, the subset of software systems has led to the discipline of Software Engineering, which shares many methods with SE in general, but also defines its own techniques specific to the software systems’ characteristics. The same applies in other engineering domains.

To identify and refine the techniques that are required to perform SoS enginering successfully, it is thus necessary to start with the characteristics, and based on them identify what implications they have on development and lifecycle management of the SoS.

As explained in the previous section, what is a system is very much in the eye of the beholder. In the same way, what is meaningful to view as an SoS is subjective. Sometimes, it makes sense to treat the system as an SoS, and apply specific techniques from that domain, and in other circumstances, it makes more sense to use a different abstraction. In some situations, viewing a system as an SoS may be most meaningful during the development (and evolution) phases, whereas it can be viewed as a general system once it is in operation.

2.2.1 Characteristics from literature

An intuitive definition of SoS is *independent collaborating systems*. Using SE terminology, the system-of-interest would be the SoS itself. Its system elements are referred to as *constituent systems*.

An often used characterization of SoS was given by Maier (1996). He uses five dimensions:

1. *Operational independence of the elements*. The constituent systems can operate independently in a meaningful way, and are useful in their own right.
2. *Managerial independence of the elements*. The constituent systems not only can operate independently, but they do operate independently even while being part of the SoS. They are acquired separately.
3. *Evolutionary development*. The SoS does not appear fully formed, and functions and purposes are added based on experience.
4. *Emergent behavior*. The principle purposes of the SoS are fulfilled by behaviors that cannot be localized to any individual constituent system.
5. *Geographical distribution*. The constituent systems only exchange information and not substantial quantities of mass or energy.

Later, the same author (Maier, 1998) stresses the first two characteristics when talking about collaborative SoS.

Boardman and Sauser (2006) also identify five characteristics, which are to a large extent overlapping with Maier's:

1. *Autonomy*. A part that is integral to a system does not have autonomy, and cannot be meaningfully used outside that context.
2. *Belonging*. The autonomous constituent systems choose to belong to the SoS, and they do that because they see a value for themselves to give up some of the autonomy in order to get benefits from doing so.
3. *Connectivity*. To let the constituent systems interact, they must be connected, and unless they provide sufficiently generic interfaces, they need to be modified to provide such interoperability. Connectivity in an SoS is thus dynamic, with interfaces and links forming and vanishing as the need arises.
4. *Diversity*. Whereas many other systems strive to minimize diversity to simplify the system, an increased diversity in an SoS gives it the ability to better deal with unforeseen situations during its lifecycle.
5. *Emergence*. Emergent behavior appears in any system, and in many systems this is deliberately and intentionally designed in, and tested. In an SoS, the emergent behavior is not restricted to what can be foreseen. Instead, it should have the capability to early detect and eliminate bad behavior that emerges.

The above two lists of characteristics overlap and pull in the same direction. They do not give a precise definition of what an SoS is, and a given instance may exhibit them in varying degrees, some of them being fully there, and others only partly. It should also be noted that not all constituent systems need to be autonomous. In most situations, there will be a mix of existing, autonomous systems, and dedicated, tailor-made system elements which complement the other constituent systems in order to make the whole SoS work.

The two definitions agree that a system which consists of elements exhibiting (a) operational independence; (b) managerial independence; (c) evolutionary development; and (d) emergent behavior, is meaningful to view as a system-of-systems (SoS). It is however really the first two of these characteristics that are fundamental. The evolutionary development is to a large part a consequence of the managerial independence, and the fact that the SoS exhibits emergent behavior is just a consequence of it being a system, as explained in Section 2.1 above (see also Lane and Epstein (2013)). However, the latter two aspects play such a large role in the development of SoS, that they still merit to be highlighted.

SoS engineering can then be seen as a set of processes, methods and tools suitable for SoS. By basing SoS engineering on the four characteristics, it will be suitable at least for the core set of systems fulfilling all the four characteristics, and be gradually less relevant for systems who do not fulfill them. Apart from this, the generic systems engineering principles can be assumed to apply, so the focus of SoS engineering is on what is specific for systems fulfilling the characteristics.

Neither of the definitions bring up the aspect that SoS are usually *sociotechnical*, and in fact it may not be a strict requirements. Still, most or all SoS that are seen in practice are very much sociotechnical, and many of the challenges in developing and operating them fall in this domain. In part, this is a consequence of the managerial independence of the constituent systems, which means that the party responsible for each system has its enabling, sociotechnical systems, which need to interact with the enabling systems connected to the other constituents.

2.2.2 Consequences of the characteristics

Some observations can be made from these characteristics, which leads to consequences on the development practices for SoS:

- *Lifecycle*: The different constituent systems have different, unsynchronized lifecycles. This means that the SoS will evolve, and changes may occur on the fundamental structure of the SoS, including which constituent systems it consists of, and what the links are between them. There is also an additional lifecycle of the environment in which the SoS exists, in which other systems may evolve in ways which affect the SoS and its constituent systems.
    - *Consequence 1*: The architecture of the SoS must be focused on being open to changes, and evolve over time to encompass new situations. The architecture of potential constituent systems also should be targeted at flexibility, in particular in its interfaces.
    - *Consequence 2*: There is a need for managerial principles to ensure that the purpose of the SoS can be upheld while the system is changing.
    - *Consequence 3*: The traditional project oriented management models will most likely not work. Each constituent system is subject to its own ongoing change projects, and these must interconnect with the evolution of the SoS.
- *Ownership*: The different constituent systems may have different suppliers, who are stakeholders in both their own system and in the SoS.
    - *Consequence 1*: Decisions about the design of the SoS will in most cases result in negotiations across organizational borders. Solutions must be found that do not restrict the autonomy of any individual system, but still makes it possible to fulfil the purpose of the SoS.
    - *Consequence 2*: The liability of the SoS is shared between the organizations behind its constituent systems.

- *Value*: In an SoS, the constituent systems do not give up their autonomy to be part of the system, but they partly modify their behavior to gain benefits. The original purposes thus remain, and can be pursued inside or outside the SoS.
    - *Consequence*: There will always be a need for requirements trade-offs between the purposes of the constituent systems, and the purpose of the SoS. There must be a value created for all constituent systems, as well as for those who choose to create the SoS. The tension is both vertical (between the system level and the element level), and horizontal (there can be conflicts of interest between different constituent systems, that appear as they are brought together in the SoS).
- *Emergence*: The purpose of the SoS is fulfilled by the emergent behavior and properties resulting from letting the constituent systems interact.
    - *Consequence*: There is a need to understand principles for controlling the constituent systems' behavior to align that with the SoS' purpose. Those principles may only exercise limited restrictions on the constituent systems' autonomy, limitations which are less severe than the benefits those systems gain from being part of the SoS. Appropriate mechanisms need to be identified and understood, which can include both regulating mechanisms to minimize inappropriate behavior, and awarding mechanisms to encourage desirable conduct.

2.2.3 Archetypes

There have been attempts to identify recurring patterns, or archetypes, that are common in SoS. The most influential set of archetypes was initially proposed by Maier (1996, 1998), and then extended by Dahmann and Baldwin (2008). It is based on the authority and responsibility in managing the evoloution of the SoS, and consists of the following archetypes, as interpreted by Lane and Epstein (2013):

- *Directed*: The SoS is build for a specific purpose, and has a dedicated central management. The constituent systems retain their individual capabilities but are normally subordinated to the SoS.
- *Acknowledged*: The SoS is built for specific purpose (similar to directed), and has central management in the form of a dedicated organization. However, the constituent systems are not normally subordinated (similar to collaborative). Typically, it is a result of building an SoS out of a combination of existing and new systems. Evolution takes place through collaboration between the constituent systems' owners.
- *Collaborative*: The SoS has an agreed upon purpose, and central management, but with limited power. Typically, the central management is formed through a cooperation between the organizations behind the constituent systems, rather than being a dedicated organization for the SoS. The constituent systems collaborate voluntarily to fulfil the agreed upon purposes.
- *Virtual*: There is no agreed upon SoS purpose and no central management. The SoS behavior is emergent, and not caused by explicit mechanisms. The formation is ad hoc and the constituent systems are not necessarily known.

The virtual archetype is somewhat questionable, since it can be discussed if an SoS without a purpose is even to be considered a system. The example virtual SoS proposed in the literature is the World Wide Web.

In a directed SoS, the central management organizations typically define the design of the constituent systems, whereas in the acknowledged archetype, it reaches agreements with the organizations responsible for the constituent systems.

A few things are worth noting. First, it is perfectly possible that a specific SoS changes its archetype as a cause of its evolution. Secondly, the archetypes are primarily based on empirical data from the US military sector, and there is limited evidence regarding their general applicability to, e.g., commercial systems. Thirdly, the definitions of the archetypes are not very clear, and in particular, the dimensions used for describing them are not well-defined and not entirely consequent over the archetypes. There is thus room for further work on identifying and describing recurring pattern.

A different set of archetypes has been proposed by Jacobson and Lawson (2015) based on the reason for creating the SoS. They use the term *incident* SoS to refer to a set of constituent systems which are put together into an SoS to reactively address a certain need that has appeared, such as a military threat or an emergency that requires coordination between different rescue units. Alternatively, the SoS can be created proactively to meet a foreseen future need, such as a market opportunity, and this is referred to as an *innovative* SoS.

One structural aspect which is rarely discussed in the literature on SoS engineering is the possibility for a constituent system to simultaneously take part in several SoS. This is likely to be a rather common situation, but requires further study.

2.3 Seven key questions in the design of an SoS

Through the focus group discussions, a set of seven key questions were identified, which are essential in the design of an SoS, to scope the problem correctly and identify the appropriate mechanisms. Even though these questions are presented in a linear fashion, in practice they have to be answered in a very iterative way, dealing with all aspects simultaneously. In a way, these questions can be seen as an embryo of an SoS engineering process, which has similarities to standard SE processes, but also adaptations to SoS peculiarities.

2.3.1 *Why* is it created?

The purpose of creating a SoS is to provide an emergent capability or function which is not achievable by any of the systems in isolation. At the same time, the original purposes of each of the constituent systems should be maintained which sets a constraint on the design space of the SoS.

The design of the SoS can modify the constituent systems, to the degree that is allowed by those constraints, and to the degree to which the managerial organization of that constituent system agrees. The parts which can be changed are within the system border of the system-of-interest (the SoS, in this case). Given the nature of what can be modified, the SoS has a fluent border, which is partly negotiated as part of its development.

Since the SoS designers can only change certain aspects of the constituent systems to achieve the desired emergent behaviors, there is a need to implement control mechanisms which impose constraints on the constituent system’s behaviors. The design of the SoS thus consists of modifying the constituent system’s behavior to the degree allowed, and if necessary, also include new constituent systems who impose constraints on the other ones.

If the SoS is seen as a control system, the plant which is controlled thus consists of the complete environment, and the untouchable parts of the constituent systems. The controller is the modified parts of the existing constituent systems and any added dedicated systems.

Key questions to ask:

- What is the purpose?
- What capabilities should be provided?
- What are the existing constituent systems?
- What degrees of freedom and constraints do they have?

2.3.2 *Whose* system is it?

Some organization, or group of organizations, are the originators of the SoS, and it is through their initial actions that it starts to form. That group, or some other organization, will take the ownership of the SoS throughout its lifetime, and coordinate its development and evolution.

The ownership can take many different forms. One, which is common in military applications under the directed archetype, is that an existing organization, such as a government agency, has the ownership, and secures the participation of the constituent systems through contractual agreement with their owners. Typically, the constituent system owners are paid for modifying their systems to fit in the SoS context, and their responsibilities are regulated in the contract.

In other situations, there is no existing organization to take ownership, and one has to be formed, either as a physical organization, or a virtual, distributed one. An example is for automotive collaborative intelligent traffic systems, such as highway platooning. The owning organization takes the form of a consortium, which sets standards to which constituent systems that wish to join the SoS must adhere.

Yet another approach is when there is an existing system which provides certain service interfaces. Another organization then builds their system on top of this platform, thereby forming an SoS. The latter organization is then the owner, and the kind of agreements with the platform organization can vary. Sometimes, it is an open interface, with no guarantees but also no cost, in which case the user organization must adapt to any changes. In other cases, a contractual agreement can be used. This kind of arrangement typically occurs in web service based systems, and software ecosystems.

It is possible that the owner of the SoS also owns one or several constituent systems, but not all of them, since it would then no longer be an SoS due to the principle of constituent system managerial independence. However, it is not required that the SoS owner owns any of the constituent systems.

It should also be noted that there is nothing that prevents a system to be a constituent of several SoS. In such situation trade-offs are needed between the requirements of the different SoS's.

Key questions to ask:

- Which organization takes ownership of the SoS?
- Is it an existing organization?
- What kind of agreements are needed with the owners of the constituent systems?

2.3.3 *Who* are the stakeholders?

Given the answers to the previous two questions, it is clear that the SoS owner is a stakeholder, as are the owners of the constituent systems. In addition to this, there are some beneficiaries of the capabilities provided by the SoS. This beneficiary can be the SoS owner, or some of its clients, if the SoS purpose is to provide a new service. In other cases, it can be the constituent systems, who each benefit from being part of the SoS by improving their own capabilities.

All existing stakeholders of the constituent systems are also potential stakeholders of the SoS, since they can be positively or negatively affected by the fact that the system is now part of something greater, and has to make certain compromises.

Finally, there are other actors who can be affected by the emergent capabilities provided by forming the SoS. As an example, other traffic on the highway may be affected by the formation of vehicle platoons.

Key questions to ask:

- Who are the beneficiaries of the SoS capabilities?
- Who are the stakeholders of the constituent systems, which may be affected by them becoming part of the SoS?

- What other actors may be affected by the emergent capabilities provided by the SoS?

2.3.4 *What* should it do?

A more detailed analysis is needed of what it takes to achieve the purpose of the SoS, i.e., what functionality is needed to create the desired capabilities. Answering this question entails something similar to a requirements analysis. However, in many cases the SoS archetype leads to a situation where the requirements are not as crisp as is the case for other systems, but rather end up as vague formulations of objectives. The design of the SoS becomes more focused on reaching a satisficing solution, rather than an optimal one.

For the SoS, the communication of requirements between the involved organizations also becomes central, since the owners of each constituent system needs to take actions as a result of the requirements. Formulating the requirements also involves complicated trade-offs between the interests of the SoS and the requirements of each constituent system, which provides constraints on what can be achieved on the SoS level. Often, modeling techniques are needed as a complement to textual requirements in order to describe the SoS.

Closely related to the requirements is verification and validation (V&V) that these are fulfilled. Given the distributed nature of SoS development, V&V also becomes a distributed activity, but it requires an organization behind it. This includes to create the necessary tests for the constituent systems to ensure that they function correctly vis-à-vis the SoS, but also that the integrated SoS provides the desired emergent behavior. In part, the V&V activities can be done through simulations.

Key questions to ask:

- What are the functions of the SoS?
- What are the requirements and objectives of the SoS?
- How should requirements be communicated?
- How should V&V of the SoS be organized?

2.3.5 *How much* should it perform?

Whereas the “what” question deals primarily with functional requirements, there is a related question on how much the SoS should perform. This relates to the quality of the system, and can be expressed as a number of attributes. The particular quality attributes to use is highly dependent on the application. However, certain generic attributes are inherent in SoS as a consequence of their decentralized nature, and these include dependability aspects including robustness, safety, and security; privacy, as a result of sharing information between the systems; and resilience against changes in the environment and through the evolution of the SoS. These are all emergent properties resulting from the composition of constituent systems into an SoS, and as for the functional requirements described in the previous section, there are also trade-offs between the properties on the SoS level and the properties of the individual constituent systems.

Achieving the qualities of the SoS is important, and not doing so thus means a loss of some kind. For this reason, the qualities are associated with risks which need to be managed. This includes identifying the acceptable risk levels for the SoS, but also for the constituent systems. It is important to notice that being part of an SoS can increase the risk for the constituent systems, since they become dependent on others, but it can also decrease the risk, if the SoS design provides alternative, redundant ways of achieving different tasks, thus leading to a resilience.

Key questions to ask:

- What are the main quality attributes of the SoS?
- How can the desired levels be quantified for those quality attributes?

- How should risks related to not fulfilling the quality attributes be managed?

2.3.6 *How* should it be organized?

Based on the functional requirements and qualities, the question becomes how to organize the SoS in order to achieve them. This includes technical questions, such as what constituent systems should be included, how they need to be modified, and how they should be connected. However, an equally important part of the design space is the organizational part, which is highly socio-technical, and includes the existing organizations behind each constituent system, and their enabling systems, but also potentially newly created organizations for the purpose of managing the SoS.

The architecture, i.e., "the fundamental concepts or properties of a system in its environment embodied in its elements, relationships, and in the principles of its design and evolution" (ISO, 2011), is a central part in the SoS design. It defines the overall structure, which can follow different patterns, such as federations, peer-to-peer, common super-system, or a shared platform. It also provides the key technical interfaces, including adjustments to existing ones in the constituent systems, in order to achieve interoperability.

The design also involves functionality needed to manage the SoS. This includes the necessary mechanisms to ensure fulfilment of requirements, i.e., to achieve the desired emergent properties, but also rules for monitoring the constituent systems' behavior; actions to handle identified deviations; and rules for participating, entering, and leaving the SoS.

On the sociotechnical side, there is often a need for legal structures, such as contracts, between the participating organizations, to sort out the obligations of each party, and the compensations if those obligations are not met. This can include federation level agreements and service level agreements. Also, the managerial principles for running the SoS development and subsequent evolution needs to be sorted out. Often, traditional project models designed for a single organization may not suffice for SoS, due to their distributed nature and unsynchronized evolution.

Key questions to ask:

- What is the architecture of the SoS?
- How should interoperability be achieved?
- What mechanisms are needed for managing the SoS?
- What are the managerial principles for the evolution of the SoS?

2.3.7 *When* does it change?

The final question deals with the evolution of the SoS. As described above, the constant evolution is a fundamental characteristic of an SoS, and it can have different reasons, including needs for changes to the environment; need for new capabilities; new requirements from stakeholders; constituent systems that leave the SoS or are modified in ways which affect the SoS; and faults that occur during operation. It is thus essential to incorporate mechanisms for handling dynamic situations into the SoS, on the technical level but even more as part of the sociotechnical domain.

Changes can also incur risks for different participants, and it becomes essential to maintain trust among the parties in the SoS as it evolves. If an organization has joined the SoS in order to achieve certain benefits, such as business opportunities, and the SoS changes so that this can no longer be fulfilled or becomes uncertain, that party may choose to leave the SoS, which could lead to the destruction of the whole constellation if that party is essential.

Key questions to ask:

- What are the evolution scenarios for the SoS?
- How should evolution be managed in order to maintain trust?

2.4 Application areas

Having described key characteristics of an SoS, we will now look at example applications, that have been proposed by Swedish industry as part of the focus group workshops. Apart from these areas, there are many other examples that can be found in the international literature (see Section 3.1 below), both in the commercial industry and as part of the public services. In all these areas, the SoS perspective becomes interesting mainly due to the possibilities provided through the recent advances in information and communication technology that are underlying the digitization trend in society.

2.4.1 Command and control for defense and civilian crisis management

Command and control (C2) is commonly defined as the exercise of authority and direction by a designated individual over assigned resources in the accomplishment of a common goal. The purpose is thus to collect information from different sources in order to give decision makers an overview of the situation, and to communicate the decisions into resources that can actuate them. C2 is one of the most studied examples of SoS, where the assigned resources play the role of constituent systems. The applications are typically within the military sector, to lead a certain operation, but there are also numerous civilian applications, including dealing with crises such as large forest fires, flooding, terrorist attacks, and major accidents. Typically, the SoS is called into rapid action in a specific situation, where the needed resources are assembled. When the situation has been resolved, the resources are dissolved. However, in order to achieve this capability, the constituent systems have to be prepared in advance for becoming parts of an SoS should the need arise.

The challenges of this domain include handling the lifecycle of the SoS; setting proper requirements; describing the overall architecture; and dealing with change management, such as the phasing out of constituent systems.

2.4.2 Construction and mining

At construction sites, such as quarries and aggregates, and in mines, a number of working machines coordinate their activities in order to achieve a maximal productivity. This SoS has traditionally been handled manually, through human communication between drivers and site managers, but there is a strong trend towards technical support for site management, remote control of machines, and automation of tasks, which makes the SoS perspective increasingly valuable. This leads to challenges in defining the overall system architecture for the site operations, identifying business values, and dealing with interoperability of equipment from different manufacturers.

2.4.3 Manufacturing

The manufacturing industry is seeking similar benefits as the construction and mining domains, but starting from a higher level of automation. The German initiatives that are often labelled “Industrie 4.0”, and similar activities in other countries, such as the Swedish “new industrialization”, have a foundation in value chain optimization through the use of information technology, and this optimization thus becomes the purpose to be achieved through an SoS approach. Some of the design principles identified in Industrie 4.0 are related to interoperability, decentralization, service orientation, and modularity (Hermann, Pentek, & Otto, 2015), which are also key issues in SoS engineering.

2.4.4 Transportation

In the transportation sector, early examples of SoS approaches exist in the form of fleet management systems for trucks, and other telematics solutions for communicating data between vehicles and IT systems. However, in recent years there has been substantial research, development and standardization in the area of information traffic systems (ITS), including cooperative ITS where vehicles communicate directly with each other through short-range radio based on derivatives of the WLAN standards, and with road side units provided by the road administration authorities. Application examples of this include vehicle platooning, hazard warnings, road status information, and green-light optimized speed advisory. Further down the road are scenarios with increasing degrees of automated driving, which also require improved information about the traffic situation.

In this sector, there is a large number of vehicle manufacturers and road side administration agencies involved, which causes a need for standardization. At the same time, there is a push for rapid innovation, which can hardly wait for standards to mature, but the business value is sometimes hard to estimate of many of the features. There are also architectural alternatives to the vehicle-to-vehicle communication which has been in focus, including cellular networks combined with cloud solutions proprietary to the vehicle manufacturers, or services open to third parties. Most likely, several of these options will be used in parallel.

2.4.5 Health care

In health care, there is a need to increase information system interoperability in general, to improve the efficiency of health care providers and thus give more value for the tax payers' money. A specific need is to reduce the time in hospitals, by allowing patients to be monitored at home through IT systems and only be brought to hospital if conditions worsen. This has a benefit both for the patients but also for society by reducing the cost of hospital care. At the same time, there are very strict requirements on patient safety, as well as on the privacy of medical records. As for the transportation domain, there is also a large set of equipment and software suppliers involved, leading to a need for both interoperability standards and certification by authorities. However, the implementation is complicated by the organizational structure of the health care area, where authority is distributed over many agencies, who interact with a large number of both public and private care providers.

2.4.6 Interactions

There are many opportunities for these business sectors to interact. One is to share knowledge on how to build SoS, and also share technical mechanisms, standards, etc., that can contribute to efficient SoS engineering, independent of the domain. However, it can also be expected that once the mechanisms for SoS creation become more common, it will also become increasingly interesting for systems to collaborate across the traditional sector boundaries. Just as an example, C2 systems for civilian crisis management would benefit very much from having connections to the transportation infrastructure and health care, in order to efficiently take care of injuries. Another scenario is that the transportation system becomes a constituent system in a production chain where parts are moved from a supplier to an integrator for final assembly. In the smart city case, finally, the smart energy grid is e.g. collaborating with household appliances with the purpose of reducing energy costs and consumption.

2.5 Challenges

Based on the characterization of SoS, and some of the applications, a number of challenges will now be discussed. SoS share many properties with systems engineering in general, and many challenges from that area also apply to SoS. Here, the focus is however on the particular issues related to SoS, which can be derived from the characteristics described in Section 2.2 above.

2.5.1 Theoretical foundations

SoS as a concept has been around for quite a while, and a large body of research exists (see Section 3.1 below). However, the area still lacks a solid theoretical foundation that can be used and tested empirically.

To be able to establish such a foundation, there is first of all a need to arrive at a more precise *language* for describing and reasoning about SoS. Even though most people agree on the high-level characterization of SoS based on Maier's criteria, and especially the operational and managerial independence of the constituent systems, there is a need for further work on more detailed characterizations related to the archetypes, and also as a basis for interoperability.

The motivation for creating the SoS is usually to provide a certain capability which is not achievable by the constituent systems in isolation. This capability is thus an emergent property of the SoS. However, *emergence* as a concept is not very well understood, and in particular how to achieve a certain set of emergent properties as a result of a design activity. This includes both achieving the desired emergence, in terms of functionality and properties, and avoiding the unintended emergence which would violate requirements (explicit or implicit). Since emergence is often the result of feedback loops between the constituent systems, understanding and controlling the information flows is a key, and this makes systems thinking a fundamental basis for SoS engineering. The feedback loops includes both internally in the SoS, as parts of its operations, but also the external learning loop to the organizations that are responsible for the operation and evolution of the SoS.

In many examples of SoS available from literature, there is a focus on situations where one organization (typically a government agency) has a clear responsibility for the SoS, and recruits the constituent systems by making contracts and compensating their owners' efforts economically as captured in the directed SoS archetype. However, there is a need for a much deeper understanding of how to design the principles for interaction and compensation that leads to a desired result for all the parties involved, and which remains stable over time. Initial ideas have emerged with inspiration from *mechanism design* (also known as reverse game theory), which is an economical discipline concerned with how to device rules of a game to achieve a desired result, such as desired market properties. In a similar way, SoS engineers should design computational mechanisms which lead to the desired emergent properties (Dash, Jennings, & Parkes, 2003). In this case, the system-of-interest must include both the technical SoS and the organizations behind the constituent systems.

2.5.2 Socio-technical aspects

Even though there are many interesting and relevant technical questions related to SoS engineering, one cannot overemphasize the socio-technical nature of SoS. The SoS in general consists of a number of technical constituent systems, but also a number of users (both related to the SoS as a whole, and to each constituent system), and a number or organizations who are responsible for the development, operation or maintenance of each constituent system and the SoS as a whole. Each of those organizations usually also operate a number of enabling systems which are a pre-requisite for the operation of the constituent systems and hence for the SoS.

This makes the SoS field inherently *interdisciplinary*, requiring competence not only in engineering, but also in organizational development, business, human factors, and sociology, just to name a few. Many of the decisions related to SoS will in fact materialize as negotiations between the involved organizations, and the engineering processes and methods must be designed to take this into account.

In light of the rapid digitization of society, and the *automation* this involves, we enter a state where the borders between the technical and human parts of the SoS will constantly evolve at a rapid pace. One could then assume that this will make the SoS an increasingly technical discipline. However, this is not likely to be the case. Instead, the digitization mainly opens up new design options and trade-offs between automatic, semi-automatic, or manual solutions, and this will just increase the interdisciplinary challenges. In particular, semi-automation changes the roles of the humans, allowing them to work at higher level of abstractions, which can lead to new and unexpected results.

2.5.3 Architecture

In the whole field of SoS, architecture appears to be the most studied topic, and remains a challenge also in the future. Many of the design decisions for the SoS are at the architectural level, involving the structure and relations between constituent systems, the principles for their interactions, and so on. Klein and van Vliet (2013) recently did a literature review of about 200 papers related to SoS architecture. However, they conclude that the field is still immature, and identify a number of topics that require further research, including platforms, business aspects, and architectural knowledge and methods needed for the analysis, design and evolution of SoS architectures. Many of these conclusions echo the route previously followed by researchers in software architecture, including the authors of that study.

The particularities of SoS lead to many challenges beyond those enlisted in Klein and van Vliet's study. A recurring pattern in the SoS literature is the use of layered architectures, where each layer is providing a service interface to the ones above it. Typically, the physical entities are controlled by individual constituent systems at the bottom, then there are layers for logical entities, services, and at the top capabilities provided by the SoS. The layered architecture is an abstract structure, and one concern becomes how to allocate different elements in that structure to constituent systems, in order to realize the intended emergent capabilities.

Another aspect of concern for the SoS architects involve the communication structure to use. In part, this depends on how the functionality has been allocated to elements, but more general patterns also exist. Alternatives include peer-to-peer communication between the constituent systems, or more centralized solutions over servers or even cloud solutions. Increasingly, the constituent system is being connected to a private cloud solution of the organization owning or managing it, and a further alternative then becomes communication between the constituent systems by connecting their respective private clouds to each other. Efficient design and management of the communication usually also requires a runtime platform that provides services to the applications.

One area which appears to have been fairly neglected in research is the problem of how to *prepare for constituency*, i.e., how to ensure that a system can becoming a constituent system of some as yet unknown SoS with a reasonable effort. Essentially, this means that the architecture of any system should be designed with mechanisms that allow adaptation of both its interfaces and behavior to fit a certain SoS. It has been argued that this does not only require communication interfaces, but also a flexible and dynamic way of adding software to the system (Axelsson & Kobetski, 2013).

The architecture also needs to support general methods for managing SoS. This includes procedures for dynamic formation and dissolution of federations; means of addressing other constituent systems; supervision; fault handling; security protection; and conflict handling (Axelsson & Kobetski, 2014). These procedures could form part of a runtime infrastructure together with principles for communication, which could all be centralized or distributed, depending on different requirements and constraints on the SoS. Apart from these general considerations, a particular SoS has to define and enforce its own rules for the constituent systems, to ensure that they all behave in a way which leads to the desired emergent properties.

2.5.4 Modeling and simulation

Modeling and simulation are part of the standard toolset for engineering, and also play an important role in SoS development. The models can serve a purpose primarily as a documentation tool for engineers, as is common with software engineering *modeling languages* such as UML. For systems engineering, UML has evolved into SysML, and this is also advocated as an appropriate tool for SoS. However, it is not obvious how good such notations are for describing emergent properties, issues related to the managerial independence, and to various lifecycle aspects. A good modeling notation should allow a simple, yet accurate, description of the important issues, and it has not been thoroughly evaluated what notations are most appropriate for SoS.

For the architecture, the systems engineering tradition in the defense sector has contributed with a number of *architecture frameworks*, starting with the US C4ISR framework, which evolved into DODAF, and the UK MODAF. These were then unified into the UPDM. As a next step, it has been decided to further evolve this into the Unified Architecture Framework, aiming to become an OMG standard with broader applicability beyond defense applications. What characterizes all these frameworks is their very high complexity, giving a high threshold for use. For very large, complex systems with a tight integration, this may be motivated, but a challenge is to complement this with light-weight agile approaches to architecture descriptions. This should be driven by a cost-benefit analysis of the application of such frameworks.

The modeling languages and frameworks described so far focus of statically capturing the structure, and to some extent behavior, of systems. However, the emergent properties that are the key to the success of an SoS are mostly dynamic, and require *simulation* to analyze. In the literature, two concepts for SoS simulation dominate, namely Discrete Event System Specification, DEVS (Zeigler, 1987) and Multi-Agent Simulation, MAS (Ferber, 1999).

DEVS is primarily a finite state machine based simulator, where a lifespan can be associated with each state. The lifespan can be a random distribution, allowing for non-deterministic models. There are also concepts for hierarchy, and various extensions for continuous time systems, etc.

MAS is more of a concept than a formalism, and many different variations exist. The key is the concept of an agent, which is at least partially autonomous, and which has a limited and local view of the complete system. The model consists of a number of agents which can communicate with each other, without any central authority. The system can be simulated to explore the emergent properties that result from the behavior and communication of the agents. As can be seen, these characteristics are similar to those of an SoS, which makes MAS an attractive concept in this context. However, many of the common examples of MAS usage are for simulations of a very large number of similar agents with simple behavior. For SoS, a much more common case is to have a limited number of different agents, each with very complex behavior, and there appears to be limited evidence on the applicability of MAS to such situations.

An alternative to building specific models of the SoS, including the creation of models for the constituent systems, is to apply *co-simulation*. With this approach, existing simulation models (possibly in different formalisms) of the constituent systems are integrated by integrating the different simulation tools. A common approach to this is the High-Level Architecture (HLA), as described in IEEE standard 1516 (IEEE, 2010). HLA provides a standard for data exchange and time management which can be used for the integration of simulation tools into a federated simulation. It allows integration of tools with different models of computation, and permits multi-rate simulation. Due to the federative design, HLA also illustrates design principles that are useful to consider for the "real" SoS, and not just the simulation. This includes the different models that are part of the federation agreement (Möller, 2012). There exist both commercial HLA simulators, such as the one provided by the Swedish company Pitch Technologies, and open source research solutions, such as CERTI (Noulard, Rousselot, & Siron, 2009).

Another more recent approach is the Functional Mockup Interface (FMI), which provides a standard API for packaging models into software components that can be integrated into a larger simulation. The focus is on mechatronic simulations where both discrete and continuous models are integrated. FMI, however, does not standardize the actual execution mechanism, that handles data exchange and time management of the overall simulation. For more information about the differences and similarities between HLA and FMI, see Yilmaz *et al.* (2014), Neema *et al.* (2014).

Important needs in the co-simulation area relate to the possibility to share simulations as black boxes, since the owning organizations may not wish to release all intellectual property of their products as part of the SoS integration.

Modeling and simulation is also tightly connected to *visualization* of the results, in particular of the emergent properties. The interactions of different properties and functions can sometimes be complex, and for evaluators and decision makers, it is important to clearly show the effects of different decisions, as evaluated in simulations or through operational data, both at an aggregated and detailed level. This appears to be an unexploited field.

2.5.5 Interoperability

Interoperability can be defined as the ability of two or more systems or components to exchange information and to use the information that has been exchanged (IEEE, 1990). At the lowest level, this requires *syntactic* (or *technical*) interoperability, which means that the involved systems use the same data formats, protocols, etc. If this has been achieved, the next challenge becomes *semantic* interoperability, meaning that the ability to interpret the information exchanged in a meaningful and accurate way. This requires a common information model, in the form of a data dictionary or *ontology*. The syntactic and semantic interoperability does not assume any particular knowledge about the other systems that are involved in the information exchange, but it is possible to extend the interoperability concept to also include such knowledge, leading to *pragmatic* interoperability.

Beyond the technical and semantic levels of interoperability, the European Union has defined a European Interoperability Framework for European Public Services, which also includes organizational interoperability, which coordinates the processes of the involved organizations, and legal interoperability, where the legislation is aligned (European Commission, 2010). These concepts have been further refined in Sweden through the work of the eGovernment delegation (E-delegationen, 2015), which also look into architectural directions in the field of public services.

Other examples of frameworks for interoperability include the NATO Interoperability Standards and Profiles, NISP (NATO, 2014) for federations of information systems; and the US National Information Exchange Model (NIEM, 2015), primarily driven by government agencies. On the commercial side, similar initiatives exist in many application domains, to standardize on both the syntactic and semantic interoperability levels.

A major challenge regarding interoperability is the slowness of standardization processes, which hampers both innovation and the capability to respond to incidents. More research and development would be needed to find more flexible means for rapidly achieving interoperability. The evolutionary nature of SoS stresses this need even further, since it cannot be expected that information models and principles for exchange will remain stable over the lifetime of the system.

2.5.6 Trust

In most cases, SoS are used for purposes that are critical, either directly through the control of critical physical or other processes, or indirectly, through the decisions made by users based on the information provided by the system. For this reason, trust in the SoS becomes a major issue, which has several dimensions.

A first dimension is *dependability*, which is commonly defined as the ability to avoid service failures that are more frequent and severe than is acceptable (Avizienis, Laprie, Randell, & Landwehr, 2004). It is a function of:

- *Availability*: readiness for correct service.
- *Reliability*: continuity of correct service.
- *Safety*: absence of catastrophic consequences on the user(s) and the environment.
- *Integrity*: absence of improper system alterations.
- *Maintainability*: ability to undergo modifications and repairs.

Closely related to dependability is *robustness*, which is commonly defined as the degree to which a system or component can function correctly in the presence of invalid inputs or stressful environmental conditions (IEEE, 1990). Avizienis *et al.* (2004) considers this to be dependability with respect to external faults, which characterizes a system reaction to a specific class of faults. However, in the field of robustness engineering, robustness is considered to be insensitivity to noise, and it is common to also consider internal noise factors, such as variability in manufacturing, or changes over times (caused by wear out, fatigue, etc.), in addition to external noise factors, such as customer usage, environment, and interactions with other (sub-)systems. For SoS, robustness is essential in the perspective of the overall capability, to ensure that it can be maintained even when some constituent systems are not performing as intended. However, it is also important for the constituent systems to maintain their operational independence even in the context of an SoS where other parts are deviating from the agreed behavior.

A third dimension is *security*, which is defined to be the confidentiality, availability, and integrity of data (Avizienis et al., 2004). Here, *confidentiality* is the absence of unauthorized disclosure of information, whereas availability and integrity is as defined above, but with a focus on *authorization*. Obviously, the creation of an SoS requires that constituent systems open themselves up for certain interactions, and security is therefore an essential ingredient.

Related to security is also *privacy*, which is basically the individual's right to keep his or her data to himself or herself. In other words, data entrusted to the system should be used in an appropriate way. There is a number of legal aspects related to privacy, limiting both what information an individual has the right to consider private (and what must be provided to authorities), and what rights to protection the individual has when the data is entrusted to an organization. For SoS, the particular challenges lie in the fact that the constituent systems will exchange certain data to achieve the overall purpose. If a user has entrusted a constituent system with certain data, and that data is exchanged with another constituent system, this may lead to a breach of privacy.

In the context of SoS, there are a number of links between these attributes related to trust. For instance, safety requires security, since unauthorized tampering with the system may lead to catastrophic consequences. Privacy is in general also dependent on security.

For SoS, particular challenges related to trust are a result of the operational and managerial independence of the constituent systems, but also of the evolutionary nature of the system, where the capability must be maintained even as the SoS is evolving. But it also puts requirements on the ways of working to achieve trust. This can be exemplified with ongoing developments in the safety area. Traditional methods have assumed a top-down development, where threats to safety are analyzed through a cause-effect mapping from component failures. Leveson (2011) argues, inspired by earlier work by (Rasmussen, 1997), that this is insufficient for today's complex systems which are to a large extent based on software, and instead, an approach based on systems thinking is required, where the objective is instead to control the system towards safe behavior. Others have argued for more dynamic approaches to safety analysis, to take into account operational data and ensure that safety is upheld even under changing circumstances (Denney, Pai, & Habli, 2015), and the use of agent based simulations to understand the implications of emergent behavior on safety (Alexander & Kelly, 2013). All these modern developments in the safety area can serve as inspiration for achieving other dimensions of trust in SoS.

2.5.7 Business and legal aspects

The formation of an SoS is initiated to fulfil a certain purpose, and in most situations, there has to be a business case present for doing so, where the perceived benefits are compared to the expected costs. Due to the nature of the SoS, and in particular the managerial independence, this business case does not only involve the overall purpose, but also the involvement of the organizations responsible for the constituent systems. In other words, there have to be gains for all involved parties.

In current SoS research, business aspects are not very pronounced. Possibly, this is due to a bias towards government driven SoS, in particular from the military sector. Often, these systems are of the directed archetype, where there is a central organization responsible for the management, which recruits the constituent systems through an acquisition process. The organizations behind the constituent systems can then be supposed to be compensated economically for the costs incurred by participating in the SoS.

However, for commercial systems, and systems of other archetypes than directed, much more options for business models exist, and it is a challenge to understand what such models are suitable depending on the situation at hand. It requires a mapping of the value streams and payment streams. In such scenarios, an organization may want to make its system a constituent of an SoS, since having access to data from the other participants can increase the functionality or performance of that constituent system, which can then attract more customers or motivate a higher price. In such situations, there is no need for any monetary transactions between the participating organizations in the SoS.

The business aspects are obviously important when setting up the SoS, but they also become a part of the operation and evolution of it. The SoS defines certain rules of conduct for the constituent systems, including requirements on quality of service, and these have to be continuously enforced during operations, and deviations need to be managed. There can be both “carrot” and “stick” approaches to this, i.e., rewards for good conduct and punishments for the opposite, both in terms of financial benefits, but also in other benefits, such as being rewarded by having higher priority to SoS services, more information available, etc. These aspects have also been research in relation to software ecosystems, an area which is briefly described in Section 2.5.3 below. However, when introducing carrot and stick mechanisms in the SoS, it is a challenge to understand the emergent properties that this could lead to. Systems thinking has to be applied to see how a certain mechanism influences the behavior of the constituent systems, and hence affects the capability of the SoS as a whole.

Business models involving more than one organization, which is by definition the case in SoS, often leads to the need for *legal* contracts to regulate the agreements made between the organizations, and to stipulate the compensations for breach of agreements. This involves different operational issues, such as quality of services, but also has to take into account the situation when a constituent system permanently leaves the SoS. Other organizations could have invested in their own systems to make them part of the same SoS, with the assumed compensation of getting benefits from the SoS, and those benefits could disappear or be reduced when other parties leaves the SoS. In other words, entering into the SoS must take into account the risk that the SoS ceases to exist, and contractual (and other) mitigations to that risk are needed. Such mitigations could include *certification* of constituent systems, where an organization is given the task of securing the correct behavior of those systems prior to allowing them in the SoS, to reduce the risk of them causing damage to others.

The legal aspects could also include *liability*, in relation to the different aspects of trust explained above. Assume that the SoS provides a certain capability, but fails to deliver that capability more often or more severely than is acceptable. This could for instance be the case when the SoS causes a catastrophic accident. As described in the previous subsection in relation to safety, such failures can be seen as emergent behavior of the SoS, rather than being caused by a single constituent system, and in those cases it can be very difficult to sort out responsibilities between the involved organizations.

2.5.8 Processes and methods

The evolutionary development of a socio-technical SoS differs in many respect from that of a general system, at least as the development process is usually viewed in the systems engineering community, and has been encoded in standards such as the ISO 15288 (ISO, 2008). Again, it is the operational and in particular managerial independence of the constituent systems that makes a difference, as described in Section 2.3 above. An SoS is usually composed in part of already existing system, who can be mildly adapted to fit in the SoS context, but still retain most of their previous behavior and properties. This makes SoS engineering much more *integration driven* and *bottom-up*, than traditional systems engineering, which is mainly top-down and focused on tackling complexity through decomposition. Even more than for general systems, the SoS design space incorporates humans and organizations, including their enabling systems, who will often implement the mechanisms needed to keep the SoS working in periods of evolution.

Major challenges exist in the *cross-organizational* work needed to conceive an SoS, where much of the decision making is manifested through *negotiations* between the organizations, aiming at finding acceptable trade-offs between the common interests of the SoS, and the interests of the individual constituent systems. This requires a well-functioning flow of communication between the organizations, including feedback loops. Clearing out who manages the SoS as a whole, and the individual constituent systems, is essential. Then, the appropriate organizational mechanisms must be institutionalized, such as a change management board for the SoS. It should be noted that just as the SoS can evolve, so can the management, and it is not necessarily the case that the same organization has the management responsibility during initial development as in the later evolution and maintenance. The appropriate models for project management and change management needs to be further investigated, and it can even be disputed if the concept of a "project" is meaningful for this kind of development, or if other structures would be more effective.

Traditional systems engineering is to a large extent driven by *requirements*, but for a SoS, there is less likely to be a set of formalized requirements, and instead a set of loose goals or ambitions replace them. This means that the development process cannot try to achieve optimization, but rather a best effort leading to satisfaction. This also has implications on *quality assurance*, which in systems engineering usually is closely connected to requirements, who are used to establish the necessary testing procedures. It can be expected that SoS quality assurance will be a more dynamic activity than for general systems, with more reliance on monitoring actual behavior, since the requirements are lacking as is the detailed knowledge about the behavior of the constituent systems. Systems thinking needs to be applied, by setting up appropriate limits for constituent system behavior with respect to quality, and designing control mechanisms that keeps the SoS within those bounds, similarly as described for safety by Leveson (2011).

Quality is closely related to risk and trust, and the risk management is also a challenge for an SoS, due to the dependence on constituent systems that are not fully controllable. However, an SoS approach can also give possibilities, by providing multiple alternatives for carrying out a certain task through the incorporation of several constituent systems which can perform the same task. In this way, resilience can be increased.

2.5.9 Standardization

As has already been discussed in relation to interoperability in Section 2.4.5 above, standardization is important. Good standards assist by giving a common and clear nomenclature, which can be shared by the participating organizations. It can also be used to capture the best practices across organizations and domains, which is often the case for process-oriented systems engineering standards. Technical standards makes the reuse of solutions possible, and allows the creation of pieces that can fit together. To a large extent, these standards are a matter of efficiency, by avoiding to constantly reinventing the wheel in slightly different, and incompatible variants.

However, standardization is also a very slow and cumbersome process. A good standard has to be general enough for reasonably wide-spread usage, and at the same time sufficiently concrete to be useful in practice. Finally, it must also be concise enough to be accessible to potential users.

All these issues pose challenges to the SoS field. When it comes to methods and processes standards, it does not appear that the area has matured enough to capture what is the general, widely applicable best practice. When it comes to technical standards, there is a good foundation in standards for, e.g., communication protocols, at a lower level, but waiting for standards on higher application levels is often not acceptable, at least not in commercial settings. The key is most likely, as discussed in relation to architecture in Section 2.4.3, to provide flexible mechanisms which can make the SoS adapt to coming standards during its evolution.

2.6 Related areas

In this report, the focus is on SoS as defined by the participants in the international research and practitioners community which use that term. As will be seen in the next chapter, this community has a strong heritage from systems engineering, often with applications in government-driven areas such as defense. However, there are a number of other communities which also work with systems that can be characterized as SoS, but which use different terms, to emphasize other aspects than is traditionally focused in SoS engineering. In this section, four such areas will be presented. It is not uncommon that a single SoS can be seen as an instance of each of these four areas, but they bring different perspectives, which means that there is a benefit in increased interaction between the different communities.

2.6.1 Cyper-physical systems

A cyber-physical system (CPS) can be defined as a system of collaborating computational elements controlling physical entities. The term was introduced less than ten years ago, and can be seen as an attempt to bring closer together the perspectives of control engineering and embedded systems, and to add to that the communication between systems (Broy & Schmidt, 2014). A CPS can be seen as a special class of SoS, where there is an element of control of physical entities, which puts stringent requirements on safety and timeliness.

2.6.2 Internet of things

Similarly to CPS, Internet of things (IoT) takes a perspective where physical entities are equipped with sensors and software, which makes it possible to connect them to other entities through the Internet. Whereas CPS focuses on control applications, much of the work within IoT has been related to massive deployment of sensors, and how to resolve communication issues. The focus is on machine-to-machine communication, although end-user interfaces are also considered. The emphasis is thus technical, and the IoT area can benefit from interactions with SoS by improving the understanding of how to build complex systems out of the basic technical elements.

2.6.3 Software ecosystems

Software ecosystems also share many challenges with SoS. Here, it is assumed that an organization referred to as the keystone provides a technical platform, on top of which other organizations called niche players can build their software products (Manikas & Hansen, 2013). There is thus a managerial independence of the different elements, but often, the niche player's software is dependent on the platform, and do not necessarily have an operational independence. Typical examples are the ecosystems formed around the Android and iOS operating systems, but many other examples exist. Much of the focus in this research is on how to perform software development in distributed organizations, dealing with the interrelations between the keystone and niche players. Also, the business aspects are important, and in particular how to achieve open innovation by opening up a product to become the platform in the ecosystem. As noted by Klein and van Vliet (2013), there is very little connection between software ecosystems and SoS, and one of the few exceptions is the work of Axelsson, Andersson, and Papatheocharous (2014).

2.6.4 Enterprise architecture

Enterprise architecture (EA) deals with how to organize the overall information system of an organization, and the original conception of this area is usually attributed to the paper by Zachman (1987) who presented a number of views for analyzing this architecture. EA can be seen as the asset owner's side of system development and maintenance, and whereas the architecting of a single system is often compared to the architecting of a building, a more proper metaphor for EA is probably city planning. Typically, EA deals with the relations between business goals, processes, information, and technology on the complete enterprise level. Even though the focus is often internal to one organization, the organizations in question are usually so large that it is appropriate to view them as consisting of several organizations, each owning their own systems, and EA is therefore closely related to SoS engineering.

3 Research frontier

Chapter summary. *Internationally, the SoS field was established some 10-15 years ago, and is dominated by US researchers, with a very strong focus on military and space applications, and with a background in systems engineering methods. A large number of people are involved, but few persons focus on the area, and citations are fairly low compared to other fields. Some of the key research topics include architecture, modeling and simulation, integration and interoperability, communication, sustainability, and safety and security. There are signs of immaturity within the research area, with only limited use of systematic empirical methods that are common in other domains, and where new research results are not building systematically on previous research.*

In comparison, Sweden has entered the research area much later, and only now is attention growing. As is the case internationally, few researchers focus on SoS, and many of them do not even call their research SoS. Activities are scattered over many organizations throughout the country. Many of the researchers in SoS in Sweden come from a background in Software Engineering or Control Engineering, and this is in contrast with the international research, which has its basis in Systems Engineering. The research topics studied in Sweden are partially the same as internationally, but some areas are more pronounced, and this includes business aspects (in particular innovation and software ecosystems), control systems, governance, and IoT. However, there is little research in Sweden on the underlying, fundamental principles of SoS engineering. This is likely to be in part a consequence of the funding strategies currently implemented. A SWOT analysis shows a broad but scattered research community lacking critical mass. There is a high competence in software and control engineering, and in empirical research methods, but the lack of systems engineering competence is alarming.

An important part of the agenda project was to establish the research frontier of the SoS area. This included the international research, which was conducted as a literature mapping described in the next section. Also, a survey was made of Swedish research actors, presented in Section 3.2.

3.1 International research

SoS Engineering has been an area of active research during a few decades, and a substantial body of literature has emerged. Given this development, we find it interesting to stop for a minute, and reflect on where we are, what has been accomplished, and what is meaningful to do research on to meet future challenges. What do we really know about how to engineer SoS? How can research better support practitioners in dealing with the future challenges?

To provide at least a partial answer to these questions, we have conducted a study of the research literature in the SoS field with the objective of providing an overview of the research area, which has also been published at the leading conference in the field (Axelsson, 2015a). This included which topics have been researched, and who is engaged in the research community.

Based on the review results, some observations were made about the topics, such as which were missing, and what should be the focus of future research, and on how the community could develop to be able to advance the state-of-the-art even more rapidly and improve research quality.

The remainder of the section is structured as follows. In the next subsection, the methodology called systematic mapping is introduced, and we explain how it was applied in this case. Then, in Section 3.1.3, the results from analyzing collected data are presented. These results are then discussed further in Section 3.1.4, and the main conclusions are summarized in the final section.

3.1.1 Method

To bring light to the research questions of this section, we need to dig into the research literature, and for this two established methodologies exist. The first, and most common one, is a systematic literature review (Kitchenham & Charters, 2007), where the papers relevant to a specific research question are identified and read in detail, resulting in a summary of the results. The second approach, called systematic literature mapping (Petersen, Feldt, Mujtaba, & Mattsson, 2008), is shallower, and aims at giving an overview and structure to a broader area. Given the nature of this work's objectives, the second method was used.

In the next subsection, this generic methodology is explained more in detail, followed by a summary of how it was applied in this work, in terms of specific research questions, data collection, and data analysis.

3.1.1.1 Systematic mapping

A systematic mapping study, according to Petersen *et al.* (2008), aims at building a classification scheme and structure of a research field. The analysis focuses on frequencies of publications for categories within the scheme, leading to a picture of the coverage of the research field. The methodology, in summary, consists of the following steps:

1. Define the research scope, and the detailed research questions.
2. Conduct literature search for primary studies.
3. Screen the resulting set of papers to identify relevant ones.
4. Build a classification scheme, by identifying keywords in the abstracts of the papers.
5. Extract data from the papers, and classify them according to the scheme, resulting in a map of the area.

We followed the above steps in this work, and in the following subsections, the details will be explained.

3.1.1.2 Scope and detailed research questions

The literature of interest in this study deals with engineering of SoS, and the overall research objective is related to the overall structure of this research area, as described in Section 1. In more detail, the following research questions are emphasized:

1. How has the field SoS developed over time? The metric we use is number of publications per year.
2. What is the geographical distribution of SoS research? The metric is the number of publications per author country.
3. Who are the leading researchers in the field? Metrics are the number of publications, the current number of citations, and the h-index, which is a combination of the two.
4. Which are the key papers in the area? The metric is the current number of citations per paper.
5. Which are the publication sources (journals, conferences, etc.)? The metric is the number of publications per venue.
6. Which are the main application areas? The metric is the frequency of papers being classified in each application area, as defined in the scheme.
7. Which are the most important research topics? The metric is the frequency of terms from the classification scheme.

3.1.1.3 Data collection

The data for this study was extracted from the database Scopus, which is provided by Elsevier but also contains data from many other publishers. It claims to be the largest research database in the world, and an initial sampling confirmed that it did indeed contain data from many of the sources where we had prior knowledge of SoS literature appearing. A drawback of the database is its focus on recent literature, primarily after 1995, but since we expected the bulk of work in SoS to be after this date, it was considered a minor problem. Scopus has previously been shown to give results of higher quality compared to open databases such as Google Scholar (Falagas, Pitsouni, Malietzis, & Pappas, 2008), which was also a factor in the decision on which database to use.

The search string used was simply “system-of-systems”, appearing in the title, abstract, or keywords fields of the database, for any publication year. The database was intelligent enough to also include results using other ways of writing the term, such as “system of systems”.

The results were exported to a text file, containing all available data fields in the database. This file formed the basis for the further analysis. The data collection was performed on January 8, 2015, and resulted in 3274 papers.

3.1.1.4 Screening

A screening was performed on the data to check for relevance. It turned out that 112 of the papers did not have any authors listed, and a closer inspection revealed that these were references to entire proceeding volumes. Those records were thus removed. A further limitation was to remove papers written in other languages than English, removing a further 140 papers (125 of them were in Chinese). The number of papers carried forward to analysis was thus 3022.

3.1.1.5 Classification

Our previous experiences with systematic literature reviews and mappings, is that they become very time consuming if done too rigorously, and there is always a risk of digging too deeply into each paper. In this work, we chose to use an iterative approach for the analysis part (step 4 and 5), where a random sample of papers was selected in each iteration. In this way, it was not necessary to manually go through all identified papers, but instead the classification scheme was built iteratively, and when the frequencies of different categories converged (which was tested using basic statistic methods such as confidence intervals for binomial distributions), the analysis stopped. In total, 116 papers were analyzed in this way. At this point, a saturation level had been reached in the number of categories in the classification scheme.

The analysis was done semi-automatically, using a script written in the programming language Python. By encoding all steps of the analysis in this script, even the manual ones, the analysis becomes completely repeatable, and will always yield the same result given the same data file. Many steps, such as extracting data about publication years, authors, citations, etc., were completely automated. The output of the script was a textual and graphical report of the detailed analysis results.

In some cases, the automation needed some manual assistance. This included the classification of publication sources, since the same source appeared with slightly different names. For example, the IEEE System of Systems Engineering Conference appeared under about 10 different names, due to various abbreviations, and sometimes inclusions of the conference subtitle. This could only be resolved manually. In the same way, keywords are not written in a standardized way, so keywords such as “system-of-systems” appear in many different variants that need manual grouping.

The classification scheme was built iteratively using a tree structure, by reading the abstracts and identifying key terms. Prior to this, a tentative first level structure was put in place. It contained the high-level areas Process, Technology, Application area, Property (capturing different non-functional characteristics and quality attributes), Tools, Methodology, Business, and Organization. Most of these areas turned out to be meaningful, and subareas to them were added as the iterative analysis proceeded.

During the manual classification, some papers were also classified as irrelevant if the abstract revealed that they were out of scope. A typical example of this was when they mentioned SoS as a potential application area, but without really contributing to SoS engineering. Very few of these papers were totally unrelated, and it was sometimes a borderline decision.

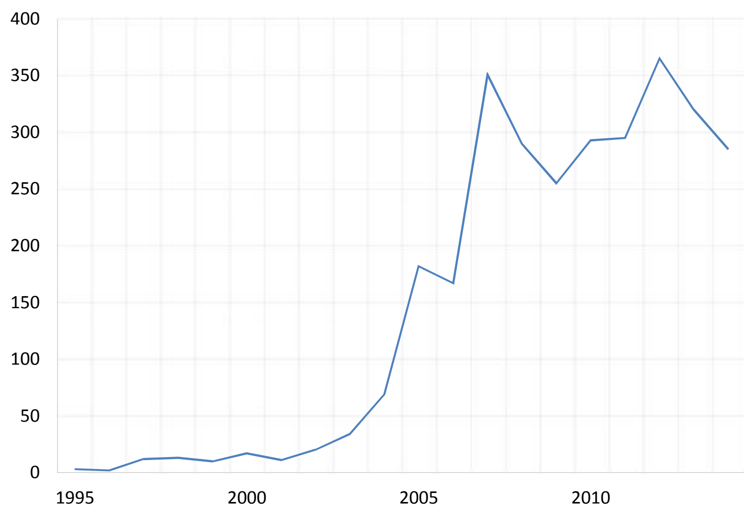

Figure 3.1. Number of papers per year.

3.1.2 Results

In this section, the results of the systematic mapping are presented. It is based on the 3022 papers identified after screening, with a detailed classification of 116 randomly selected papers, as described above. In the sample, 16 papers were classified as irrelevant, corresponding to 14% of the total literature base. This is a reasonably low number, indicating that the literature search yielded a reliable result.

3.1.2.1 Time and geography

The first research question was how the SoS field has developed over time, and this is illustrated in Figure 3.1. Since the Scopus database is focusing on recent papers, the graph starts at 1995, but when compared to other sources, papers before that date are sporadic. Since the data was extracted very early in 2015, it is not likely that the data for 2014 was completed yet, so the ending dip does not reflect a trend and if the study is redone later, this number is likely to increase. As can be seen from the graph, activity started to increased sharply around 2003-4, and then reached the current level about five years later.

The second research question concerned the country of origin. Here, the metric used was the number of publications with at least one author from that country. The result is summarized in Figure 3.2, where the first (blue) bar shows the overall count for the 15 most common nations.

As the graph indicates, US domination is almost overwhelming, with an order of magnitude more papers than each of the following nations. Among the top 15 countries, 9 are from Europe. It is worth commenting on China, and recalling that the initial screening actually removed 125 papers in Chinese. If they were included, China would be in a clear second place, and there is thus substantial research activity in this country. However, a lot of it is not connected to the international research community, due to the use of language.

The second (red) bar in the figure shows the count for the last five years, i.e. 2010-2014. The top 15 countries are still the same, but the US dominance is less pronounced, and many of the other countries actually have the majority of their publications in this period.

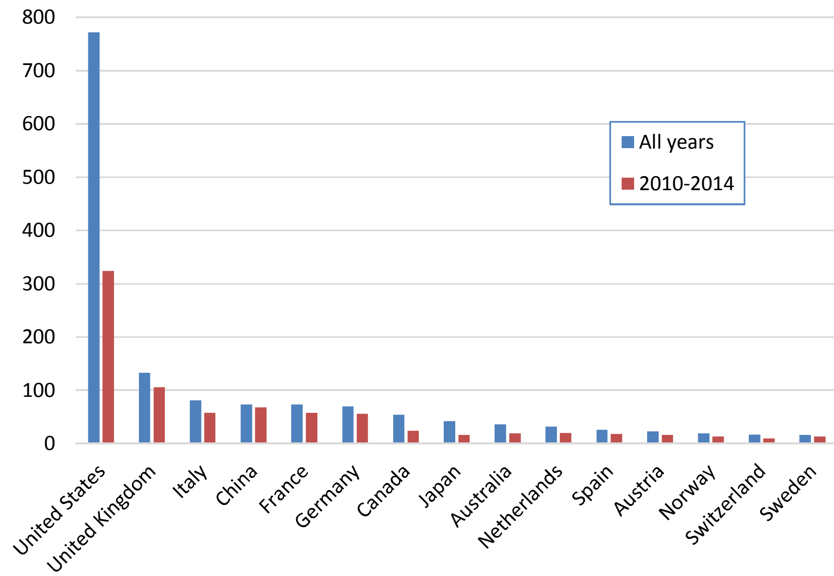

Figure 3.2. Number of papers per country.

3.1.2.2 Authorship, papers, and citations

In the data set, there are 5632 individual authors (with some reservation for variations in spelling that could lead to the same author being counted several times). On average, there were approximately 3.0 authors per paper. Around 56% of the authors were affiliated with academia, and the rest with industry, government agencies, etc.

Research question 3 concerned who the leading researchers in the field are, and this is something which is a bit hard to measure. Common metrics include the number of publications, but also the number of citations. Nowadays, it is customary to also combine those two metrics into an h-index, where h is the largest number such that a given author has published h papers that each has at least h citations.

Some authors, such as Boehm, have been highly productive outside the area of SoS. Here, we have only included citations to papers within SoS, but not citations to papers in other fields by the same author, since we are not evaluating the total contribution of these authors, but rather their contributions to the SoS field. (For the citing papers, however, no discrimination was made regarding their topic.) The same principle applies for calculating the h-index.

The 10 most productive authors in the SoS field are listed in Table 3.1, showing their total number of papers. The 10 most cited authors are shown in Table 3.2. As can be seen, DeLaurentis, Keating, Sauser, and Boardman appear in both tables.

The results for h-index are fairly low. Keating, Sauser, and Boardman each reach h = 7, with Jamshidi and DeLaurentis at h = 6. The total set of papers has h = 32.

Table 3.2. Number of citations per author.

Author	No. citations
Keating, C	307
Jackson, M	288
Keys, P	223
Sauser, B	210
Sousa-poza, A	210
Boardman, J	198
DeLaurentis, D	181
Rabadi, G	166
Boehm, B	165
Unal, R	162

Research question 4 was about the key papers in the area. The 10 most cited papers are listed in Table 3.3 (see reference list for complete details). It is worth noting that about 2/3 of the papers have never been cited.

3.1.2.3 Publication sources

Research question 5 concerned publication sources. In the data set of over 3000 papers resulting from the search and screening, the vast majority (74%) were conference publications, followed by journals (21%). The remaining papers included book chapters, reviews, editorials, etc. A more detailed view of the publication sources is provided in Figure 3.3 that indicates the number of publications covering the 15 most frequently used sources.

As could be expected, the arenas provided by the IEEE and INCOSE are the most frequented ones, but it is also interesting to see a large amount of research published by the Society of Optical Engineering. It should be mentioned that there is a very long tail in this distribution, with a total of close to 1000 source titles (about 1/3 with only one publication).

3.1.2.4 Application areas

Research question 6 concerned the most common application areas, and the metric was based on the manual classification of the 100 papers that remained in the sample after removing irrelevant papers. The results here were very clear: 21% of the papers were from the Military domain, followed by 11% from the Space area. However, there were also 18 other application areas mentioned, each with between 1-5%, including Health care, Disaster management, Aircrafts, Robotics, Power systems, etc. 67% of the papers related to at least one application area.

Table 3.3. Most cited papers.

Title	No. cit.
Towards a system of systems methodologies (Jackson & Keys, 1984)	223
System of systems engineering (Keating et al., 2003)	160
Integration of quality and environmental management systems (Karapetrovic & Willborn, 1998)	98
System of systems (SoS) enterprise systems engineering for information-intensive organizations (Carlock & Fenton, 2001)	92
A system-of-systems perspective for public policy decisions (DeLaurentis & Callaway, 2004)	84
Some future trends and implications for systems and software engineering processes (Boehm, 2006)	74
System-of-systems engineering management: A review of modern history and a path forward (Gorod, Sauser, & Boardman, 2008)	70
Critical infrastructures at risk: A need for a new conceptual approach and extended analytical tools (Kröger, 2008)	69
A theory of enterprise transformation (Rouse, 2006)	66
The emerging joint system of systems: A systems engineering challenge and opportunity for APL (Manthorpe, 1996)	57

An area worth special comments is earth observation. Many papers addressed the Global Earth Observation System of Systems (GEOSS). A number of these papers were however classified as irrelevant, since they did not relate to the SoS aspects of GEOSS, but rather to some component, algorithm, etc. to be used in that SoS.

3.1.2.5 Research topics

The final research question was about the most important research topics, as deduced by the manual classification of the 100 papers. The first area we studied was Processes, where we tried to relate the papers to different life-cycle processes. Of the papers, 56% related to processes of some kind. The ones that stood out were Modeling (22%) and Integration (17%). At a somewhat lower level, Risk management (9%), and Requirements and Design (each 7%) were significant.

A second area was Properties, and not surprisingly, a wide range of properties (30 in total) were mentioned, and many papers (43%) made reference to at least one property. The ones that were mentioned more than just a few times were: Sustainability (8%); Interoperability (7%); Cost, Effectiveness, Safety, and Security (each 6%); and Efficiency and Reliability (each 5%). Although the sample does not allow us to determine the exact ranking of these properties in the total set of papers, they are all likely to be important characteristics of the SoS research area.

The third area concerned Technology and design, to which 49% of the papers made reference. The dominating theme in this area is Architecture (23%), with Communication (14%) in a clear second place. Further behind, Sensors and Interconnections (each 7%) are also worth mentioning.

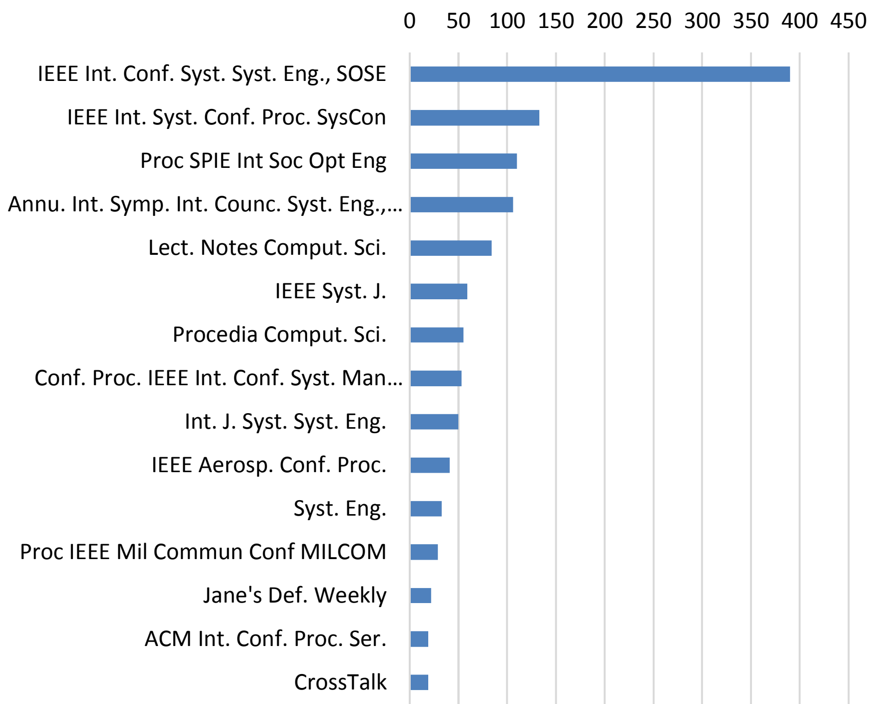

Figure 3.3. Number of papers per publication source.

The fourth area was Tools (mentioned in 20% of the papers), and the only significant finding here was Simulation (12%).

In the high-level areas Business and Methodology, no clear patterns emerged from the literature, and fairly few papers (2% and 13%, respectively) touched these topics.

3.1.3 Discussion

Based on the results from the previous section, we will now discuss certain aspects of the field. This discussion is more subjective, and based on interpretations and extrapolations from the data. The focus is on how SoS engineering research can advance further in the future.

3.1.3.1 Overall status of the research field

When looking at the research field on a high level, it is interesting to notice that this is an area that attracts a large number of people. However, half of them have contributed to only 5 papers or less. We see two possible explanations. One is that researchers from other fields occasionally touch upon the SoS subject, but do not see it as their primary concern. The other is that there are many practitioners who sometimes contribute, but their main occupation is to build real systems, and not write research publications.

Another striking observation is the citation practices. The number of citations to the most cited papers in the collection is very low, compared to other fields, and the same goes for citation count and h-index for the leading individuals. Although there are certainly excellent exceptions to this, it appears that much of the research is not systematically building on previous research, in a way that is otherwise characteristic of a mature and well-functioning research area.

One must also comment of the unusual dominance of one country, the USA. Although it appears that a shift towards a more even balance has already begun, it is vital for the field to even further reach out to the global community of researchers. In particular, links with Chinese researchers who primarily publish in their own language today, could inject new energy into the field.

3.1.3.2 Broader application areas

Another unbalance in the publications is the preoccupation with military and space applications. Although these are important, they are surrounded by very particular conditions, such as advanced acquisition models, very small production volumes, trained users, etc. At the same time, there is vibrant development in other parts of society, with research and development in cyber-physical systems, Internet of Things, and software ecosystems, that all relate to SoS. Getting closer ties with these communities would provide a broader range of example applications and building blocks, and hence lead to an improved understanding of SoS in general. This knowledge would certainly spill back on military and space applications as well. It would also be valuable to study the business models for commercial SoS usage.

3.1.3.3 Systematic use of empirical data

One of the strengths of the SoS area is that there is a strong interaction between practitioners and researchers, a fact upon which other communities would look with envy. However, it does not appear that researchers take the maximum scientific advantage of this. Most of the papers reporting real applications appear not to be based on any systematic empirical research methods, such as case studies or experiments, but are mainly providing anecdotal evidence. This makes it difficult to draw sharp conclusions, to compare different studies to one another, and to connect the data to theories.

SoS researchers should seek inspiration from the Software Engineering domain. When that domain was at a similar stage as SoS today, leading researchers advocated the use of systematic methods and basing research on empirical data. This has greatly contributed to the development of the area and are now accepted as mandatory practices for submissions to top conferences and journals.

3.1.3.4 Focus on core principles of SoS

Once systematically collected empirical data is available, it becomes possible to study and formulate sound theories that can be validated against further data. Many of the topics that stand out in the study, such as architecture, modeling and simulation, integration and interoperability, communication, sustainability, and safety and security are likely to deserve continued attention. However, researchers need to even clearer formulate in what ways these topics have to be handled differently for SoS, than for other systems. There is thus room for improving the understanding of the core principles of SoS, and connecting that to various properties, technologies, etc.

3.1.3.5 Validity of the study

As with any other empirical study, there are many threats to validity of the findings in this section as well. The selection of literature database, the search string used, the manual and automatic processing, and the use of sampling can all lead to less confidence in the results. For this reason, triangulations have been used, for instance to compare the Scopus results with searches in Google Scholar, to compare the results of the manual classification with the keywords selected by authors and librarians, and to use confidence intervals for the sample statistics. Our impression is that the overall results in Section 3 are likely to be similar even if the method would be changed in different ways.

3.1.4 Summary of international research

In this section, we have presented a systematic literature mapping of the SoS area, including over 3000 research papers. In summary, the main findings are that the field is dominated by US researchers, and that there is a very strong focus on military and space applications. A large number of people are involved, but few persons focus on the area, and citations are fairly low compared to other fields. Some of the key research topics include architecture, modeling and simulation, integration and interoperability, communication, sustainability, and safety and security.

In our view, there are signs of immaturity within the research area, with only limited use of systematic empirical methods that are common in other domains, and also that new research results are not building systematically on previous research.

To improve this situation, we would recommend the creation of an international scientific event with very high standards for submissions. This would give the leading researchers in the field an opportunity to build a community and to focus on the scientific study of SoS engineering. To build on one of the strengths of the area, namely the good connection to practitioners, the event should ideally be co-located with an existing event, such as the IEEE System of Systems Engineering Conference.

3.2 Swedish research

In parallel to the review of international research, a study was made of Swedish research, with a focus on primarily identifying the relevant research actors, and as a second step, gathering more detailed information on what topics they are studying. In the following subsection, the method used is described, followed by a presentation of the results. Then, the findings are discussed, and in the final subsection, the conclusions are summarized.

3.2.1 Method

To find out who the relevant researchers are, and what they do, different methods can be used, which can be expected to yield different results. We choose to combine several methods, and do an informal triangulation between their results to get an as accurate as possible view of the actors. As a starting point, we identified three entities that can be used to identify researchers active in the SoS area, namely funding agencies who provide funding for specific projects in defined topics; universities and institutes who employ researchers; and publication sources, where researchers disseminate the results. Surveys were sent to the funding agencies and institutions asking for information about active researchers, and once researchers had been identified, further surveys were sent to these individuals to ask about more details regarding their research. In addition, the literature base described in Section 3.1 was queried for papers written by researchers based in Sweden. In the remainder of this subsection, the steps are described in more detail.

3.2.1.1 Selection of respondents

An early step in conducting a survey is to identify respondents. Information about funding agencies who could potentially support SoS research was gathered from a summary of funding agencies[2]. This list contains 19 major research funding sources, including government agencies and public as well as private foundations, who in total provided 13,180 MSEK of funding at the time of compiling the list. Given that the focus of this report is SoS, and in particular the engineering of SoS, a number of agencies could be removed as being unlikely to support research in the area, and in the end, the following funders were contacted: Swedish Energy Agency (Energimyndigheten), Science Council (Vetenskapsrådet), Swedish Innovation Agency (Vinnova), Knowledge Foundation (KKS), Swedish Foundation for Strategic Research (SSF), and the Knut and Alice Wallenberg foundation. Together, these six actors provided 9,208 MSEK in the same period, or 70% of the total funding.

The universities were identified from a list provided by the Swedish Higher Education Authority (UKÄ)[3]. In total, there are 48 public or private universities or similar institutions in Sweden, and just as for the funding agencies, a selection was done using information on their home pages, based on the likelihood that they do research on SoS. A number of institutions are purely educational, with no own research, and they were removed. Also, some have very limited scope, such as only focusing on design, arts, theology, or psychotherapy, and they were also eliminated. In the end, 25 out of the 44 institutions

[2] *Svensk forskning – större forskningsfinansiärer*. Available from http://www.vinnova.se/upload/EPiStorePDF/SvenskForskning2009.pdf.
[3] http://www.uka.se/faktaomhogskolan/universitetenochhogskolorna.

were contacted, including all the larger universities, as well as some smaller, but with specializations that could be related to SoS.

Research is not only carried out in universities, but also in public and private research institutes, and these are a bit harder to identify. As a starting point, Wikipedia's list of Swedish research institutes was used[4]. This was complemented by information from a Swedish research portal, when searching among research actors in the natural sciences and technology[5]. By again filtering on the likelihood of being relevant, the following research institutes were contacted: Acreo, Swedish Defense Research Agency (FOI), Forestry Research Institute (Skogforsk), SP Technical Research Institute of Sweden, Swedish National Road and Transport Research Institute (VTI), Swerea IVF, Swedish Institute of Computer Science (SICS), and Viktoria Institute. To these were added two further actors, Swedish Defense Material Administration (FMV) and Royal Swedish Academy of Engineering Sciences (IVA), which are not research institutes in the normal sense, but for which there were indications that they could nevertheless be relevant in this context.

3.2.1.2 Surveys

The funding agencies, universities, and research institutes were all contacted by e-mail in December 2014 and January 2015 through the official address indicated on their home pages. The e-mails were written in Swedish, and contained a short paragraph containing information about the agenda project. It also gave a high-level definition of the area SoS: "In this area, the principles for interconnected systems are studied, each of which has its own independent purpose and individual owners, but who through cooperation can achieve new or better functionality."

The funding agencies were then asked if they are funding research in the SoS area, and if so, what projects they have funded (with indications of budget, project leader, and summary of the contents).

The universities and institutes were asked if they do research in the SoS area, and if so, who should be contacted for further information.

The organizations were given a month (in many cases including the Christmas break) to reply, which many managed to do. For those who did not, a reminder was sent, leading to replies from most of the remaining ones.

When the universities and institutes responded with contact persons, those individuals were immediately contacted through e-mail. The message contained the same introductory information as described above, and then they were asked to first confirm that they really do research in the SoS area, and if so, provide a short (5-10 lines) summary of that research.

No specific deadline was given to the individuals initially. However, in mid March 2015, a reminder was sent to all contacted persons who had not replied, and this time they were given a week to answer. Most people then replied promptly, with a few exceptions who came even later.

3.2.2 Results

The survey conducted was quite extensive, and led to a large number of replies from different actors. In this subsection, the results are summarized, starting by the funding agencies, and then universities and institutes. Then, the research topics studied will be discussed in more detail, and the responses from the reviews are also correlated with findings from the literature search. Finally, a workshop gathering many of the researchers was organized, which is also described at the end of the subsection.

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[4] http://sv.wikipedia.org/wiki/Lista_%C3%B6ver_forskningsinstitut_i_Sverige.
[5] http://www.forskning.se/forskningutveckling/aktorerao

3.2.2.1 Funding agencies

All the six funding agencies that were contacted replied. VR, SSF, and Vinnova are broad funding agencies, and they all said that they support SoS related research, although none of them currently supports any project that explicitly uses the term. SSF and Vinnova also submitted partial lists of projects that are more or less related to SoS.

KKS has a special role, in that it funds research in all topics as long as it takes place at any of the so-called "new" universities in Sweden. They indicated that some of their projects in the IT area could have a bearing on SoS.

The Energy Agency does not fund SoS research in general, but many of the hot topics in the area, such as smart cities and smart electricity grids, naturally leads to SoS issues, and in those cases the agency funds projects with applications in the energy domain.

Knut and Alice Wallenberg Foundation, finally, indicated that they do not fund research on SoS.

It is worth noting that many of the agencies had some difficulties answering the question with precision. This is understandable, given the large number of projects they handle, but it is also indicative of how research funding is organized today. Vinnova serves as a good example of this. Much of their funding today goes through programs that are very application focused, such as the Challenge Driven Innovation program (UDI) or the different Strategic Innovation Programs (SIP). Within such programs, it is not uncommon that SoS principles are applied, but it is not made explicit, and it is likely that many of those projects would have benefited from a more systematic use of SoS methodologies.

However, the unfortunate consequence of this is that there is no or very limited room for overhearing between industrial domains and application areas. Since SoS is often about breaking the barriers, and providing border-crossing innovation, it is hard to advance SoS research with this funding strategy. Further, there is no or little funding available for a systematic study of the principles for SoS engineering, something which would be highly beneficial as a foundation for the many application oriented programs.

3.2.2.2 Universities

The survey was sent to 25 universities, and 21 of these (or 84%) replied. Of the replies, 17 (81%) were positive, indicating that they have SoS related research areas. Some universities, namely Gothenburg University and KTH, replied that they do not have SoS research, but through other routes, researchers were found in those institutions that do relevant research. Also, the Swedish Defense University (FHS), did not reply, but relevant researchers were identified by other means at this university. This means that all in all, there are at least 20 out of the 25 contacted universities that do SoS related research. The universities that did not respond were FHS, Dalarna University, Karlstad University, and Uppsala University. (The details of which universities have SoS research can be found in Table 3.5 below.)

Most of the universities replied with contact information to one or several relevant researchers. In a few cases, a dean of faculty or head of department responded and gave a more general description of their research. In those cases, it is more difficult to determine exactly what and how much SoS related research they do.

3.2.2.3 Institutes

Among the institutes and similar actors, responses were received from six out of the ten contacted organizations, giving a lower response rate of 60%. This could possibly be explained by the fact that many of these organizations are not organized as government agencies, but as companies, and hence are less used to, and less prepared for, this kind of inquiries.

Five, namely FMV, FOI, VTI, SICS, and Viktoria institute, out of the six organizations indicated that they do SoS related research, whereas Swerea IVF are not active in the area. Again, there are mismatches between the responses from the central organizations and what can be learnt in other ways. For instance,

Table 3.4. SoS application areas addressed by Swedish researchers.

Application area	BTH	Chalmers	FHS	FMV	FOI	GU	HHS	HiS	KI	LTU	LU	SICS	ÖRU	Count
Healthcare	X							X	X	X	X	X		6
Automation and mobile robots		X				X			X	X	X			5
Automotive and transportation		X				X					X	X		4
Defense			X	X	X									3
Smart cities							X					X		2
Emergency response					X									1
Power systems											X			1
Logistics													X	1

as can be seen in Section 3.2.2.5 below, researchers at SP have published papers related to SoS, but SP did not respond to the survey. Responses were also not received from Acreo, IVA, and Skogforsk.

Again, the level of detail in the responses varied between different institutes, with detailed responses and contact persons being received from FMV, FOI, and SICS. VTI and Viktoria institute did not provide more details about what research they conduct in the area.

3.2.2.4 Individual researchers and topics

As described above, all the identified contact persons were asked to give a short summary of their research. In total, 51 researchers were contacted, and 41 of these (80%) replied. Out of these, 38 (93%) said that they are indeed active in the area, and gave a short description.

As for the analysis of the international research, we will now look deeper into the research, and focus on the application areas studied, and the scientific topics addressed. Table 3.4 summarizes the application areas enlisted by the researchers at different universities and institutes. The table only lists a subset of the organizations, since not all researchers made it explicit which application areas they address (and were not asked to do so). Still, it gives an indication of what areas are prioritized, and this picture is very interesting to compare with the international research as described in Section 3.1.2.4. It is quite clear that areas such as healthcare, automation and robotics, and the automotive sector are given much more emphasis in Sweden. In part this can be explained by the strong industries in these areas, and also by urgent societal needs. Defense also plays an important role in Swedish SoS research, but at a much lower level than internationally. In part, this is surely due to a much lower funding level of defense related research here, compared to, for instance, USA.

To analyze the research topics, the same structure was used as for the systematic literature mapping in Section 3.1, and the texts sent in by researchers were mapped to topics in this structure. A summary of this is shown in Table 3.5. Comparing to the international data, some areas stand out. Business aspects is one of them, and in particular in relation to innovation. A number of researchers in Sweden address this, several of them in the context of software ecosystems. Another area is control systems, where Sweden has a very strong tradition which is visible in many universities. Governance appears to also be more emphasized, in particular in connection to the defense sector. Finally, the topic Internet of Things (IoT) is totally absent from the international SoS community, but has been given enormous attention in Sweden during the last years, partly driven by the strong telecommunications industry here.

Table 3.5. SoS research topics addressed by Swedish researchers.

Topic	Subtopic	BTH	Chalmers	FHS	FMV	FOI	GU	HHS	HIJ	HiS	KI	KTH	LIU	LNU	LTU	LU	MAH	MDH	SLU	SU	SICS	ÖRU	Count
Business	Innovation		X					X						X		X	X				X		6
Methodology	Systems thinking													X									1
Process	Design						X																1
	Integration									X													1
	Modeling				X				X			X				X							4
	Operations									X													1
	Requirements	X																					1
	SoS governance			X		X					X												3
	Testing	X																					1
Property	Availability											X											1
	Efficiency										X												1
	Flexibility											X											1
	Interoperability											X		X									2
	Performance					X																	1
	Quality											X											1
	Reliability					X																	1
	Resilience																	X					1
	Safety					X																	1
	Security											X											1
Technology	Agent																X		X				2
	Architecture					X	X		X						X		X				X		6
	Communication														X						X		2
	Control systems										X	X	X		X	X							5
	Interconnections														X								1
	Internet of things														X	X	X			X	X		5
	Sensors					X												X					2
Tools	Simulation				X																		1

Among the areas that stand out in the international investigation, several are also emphasized in Sweden, including modeling and simulation, interoperability, agents-based techniques, architecture, and communication. The ones that are perhaps a bit less present is the integration process, and risk management, but this is hard to say with absolute confidence from the limited data.

3.2.2.5 Publications

Active researchers are very likely to also publish papers, and therefore it is interesting to compare the responses of the survey to the literature with Swedish authors found in the study in Section 3.1. As could be seen in Figure 3.2, there were 16 papers with at least one author with a Swedish affiliation in the literature base of over 3,000 papers. Those 16 papers are presented in more detail in Table 3.6.

There are several possible explanations to why there are so few papers in this table. One is that there are more papers that were not captured in the study, since they were not indexed by the particular database

Table 3.6. Publications by authors with Swedish affiliation.

Paper title	Swedish affiliations	Year	No. citations
Societal need for improved understanding of climate change, anthropogenic impacts, and geo-hazard warning drive development of ocean observatories in European Seas	Gothenburg university	2011	20
Vulnerability analysis of interdependent critical infrastructures: Case study of the Swedish railway system	Lund university	2011	5
Testing highly complex system of systems: An industrial case study	Blekinge Institute of Technology	2012	4
Model-based safety engineering of interdependent functions in automotive vehicles using EAST-ADL2	KTH, with industrial partners Mecel, Volvo, Mentor Graphics	2010	3
Towards an architecture for service-oriented process monitoring and control	Luleå University of Technology	2010	3
Issues and challenges in ecosystems for federated embedded systems	SICS, Linneaus university	2013	2
The Nordic Geodetic Observing System (NGOS)	National Land Survey of Sweden	2007	1
Software engineering of component-based systems-of-systems: A reference framework	KTH	2011	1
Characteristics of software ecosystems for Federated Embedded Systems: A case study	SICS, Linneaus university	2014	1
Higher-order effects of radiated interference - Challenging research domains within EMC in future military dynamic wireless communication networks	FOI	2005	0
Satellite based information to support European crisis response	Linköping university	2009	0
Modular safeguards to create holistic security requirement specifications for system of systems	TeliaSonera	2010	0
EMSO: European multidisciplinary seafloor observatory	Gothenburg university	2011	0
A new Manhattan project? Interoperability and ethics in emergency response systems of systems	SICS	2013	0
Intelligent transport systems - The role of a safety loop for holistic safety management	SP, KTH	2014	0
Reasons for bottlenecks in very large-scale system of systems development	Blekinge Institute of Technology	2014	0

used. Another is that many of the researchers might have moved into the SoS area quite recently, and this is supported by the table, where only 3 papers are older than 2010. A third explanation is that many of the researchers work in fields related to SoS, but use a different term for it.

3.2.2.6 Scandinavian Workshop on the Engineering of Systems-of-Systems

To get a more in depth understanding of what research is currently carried out, and also to give the participants a chance to meet, a workshop was organized on May 27, 2015 at SICS in Kista. The workshop was called the 1st Scandinavian Workshop on Systems-of-Systems Engineering (SWESoS). The identified researchers were invited to submit a short extended abstract, and the event was also announced using home pages and e-mail lists used by many researchers. 16 abstracts were received. 13 of these were accepted for presentation, whereas the other three were dealing with complex systems, but not SoS. The 13 papers (twelve from Sweden and one from Denmark) were each given about 20 min to present, and the extended abstracts were also published as a proceedings document (Axelsson, 2015b). Topics discussed included business aspects (software ecosystems, openness, and innovation); architecture (enterprise architecture and cyber-physical systems); principles and properties (emergence, concepts, and relations to human factors); and applications and tools (from manufacturing and healthcare). The workshop was highly appreciated by the participants, and stimulated many fruitful discussions. There are plans to organize a follow-up event, probably in the spring of 2016.

3.2.3 Discussion

The information gathered from the various surveys is very rich, and sometimes divergent. To gain a more comprehensive understanding of the situation, a triangulation has been performed which will be reported next. That will serve as an input to an analysis of the strengths and weaknesses, as well as opportunities and threats, to successful Swedish research in the SoS area.

3.2.3.1 Triangulation

The triangulation consists of comparing the results from the surveys to funding agencies, universities and institutes, and individual researchers, with the results from the literature search. Also, the participation in the SWESoS workshop has been included, since prioritizing this activity is an indication of how important the SoS area is to the actors. The purpose is to identify the most active research environments in Sweden, and the assumption is that environments that appear in many of the studies are more active than those who show up in few of them.

The result of the triangulation is shown in Table 3.7. In the table, there is one column for each data set, where a marking in the column for a certain organization is determined as follows:

- *Funding*: The organization has funding from SSF[6] related to SoS.
- *Central response*: The official response to the question sent to the organization's central point of contact was positive, indicating that there are SoS activities.
- *Individual response*: An individual in the organization has provided data about the SoS related research carried out by that individual, or by the individual's group or department.
- *Publications*: The literature mapping included references to at least one paper with an author from this organization.
- *SWESoS*: At least one person from the organization co-authored a presentation at the SWESoS conference.

[6] The reason to only include SSF in this column was because only SSF provided sufficiently precise data to determine if the projects were really SoS related. Vinnova also provided data about a large number of projects, but it was not possible with a reasonable effort to determine the relevance of each project, nor the involved organizations.

Table 3.7. Triangulation of different data sources.

University/Institute	Funding	Central response	Individual response	Publications	SWESoS	Count
Lund University (LU)	X	X	X	X	X	5
SICS	X	X	X	X	X	5
Defense research institute (FOI)		X	X	X	X	4
Royal Institute of Technology (KTH)	X		X	X	X	4
Linköping University (LiU)	X	X	X	X		4
Blekinge Institute of Technology (BTH)		X	X	X		3
Chalmers		X	X		X	3
Gothenburg University (GU)			X	X	X	3
Linnaeus University (LNU)		X	X		X	3
Luleå University of Technology (LTU)		X	X	X		3
Malmö University (MAH)		X	X		X	3
Mälardalen University (MAH)	X	X	X			3
Defense Material Administration (FMV)		X	X			2
Stockholm School of Economics (HHS)		X	X			2
Jönköping University (HIJ)		X	X			2
University of Skövde (HiS)		X	X			2
Karolinska institutet (KI)		X	X			2
Mid Sweden University (MIUN)		X	X			2
Stockholm University (SU)		X	X			2
Swedish University of Agricultural Sciences (SLU)		X	X			2
Viktoria Institute		X	X			2
Swedish National Road and Transport Research Institute (VTI)		X	X			2
Örebro University (ÖRU)		X	X			2
Swedish Defense University (FHS)			X			1
SP Technical Research Institute of Sweden				X		1
Umeå University		X				1
Acreo						0
Dalarna University (DU)						0
University of Gävle (HiG)						0
Halmstad University (HH)						0
Royal Swedish Academy of Engineering Sciences (IVA)						0
Karlstad University (KAU)						0
Skogforsk						0
Swerea IVF						0
Uppsala University (UU)						0

The table lists the organizations sorted first by number of markings, and secondly in alphabetical order for equal number of markings. One should be careful at drawing too far-reaching conclusions from this table, due to the incompleteness of data it is based on. Still, it is reasonable to assume that the organizations in the upper parts have a reasonable activity in SoS, whereas those in the lower parts do not. For those in the middle, some activities exist, but more data is needed to determine the level and direction.

When looking at the organizations in the upper part of the table, and studying in more detail who the researchers are in these organizations, it becomes obvious that the SoS area is approached by researchers in Sweden from two directions. One is from Software Engineering, which is natural since the focus when building SoS is information integration, which requires software solutions. The other direction is Control Engineering, and this is also natural, since many of the applications of SoS involve the integration of control systems. Almost all the organizations in the upper part of the table are well-known to be internationally strong in at least one, and often both, of these disciplines.

However, this also shows a striking difference between Sweden and the international SoS community, where the latter is very much based in a Systems Engineering tradition. That tradition is to a large extent lacking in Swedish academia, and Software Engineering and Control Engineering are probably the closest substitutes we have. A consequence of this has been that research in Sweden focus on areas such as Cyber-Physical Systems (CPS), Software Ecosystems, Internet of Things (IoT), etc., which are natural extensions of the previous research in those groups, but which lack important elements of SoS. In particular, many of the socio-technical aspects, related to management of the SoS lifecycle, and change management, tend to fall into the background of more technical matters.

3.2.3.2 SWOT analysis of Swedish research

As a basis for the actions in the research and innovation agenda, which is discussed in Chapter 4, the present state of Swedish SoS research will be discussed in terms of strengths, weakness, opportunities, and threats. The strengths and weaknesses are a result of an internal analysis of the research, whereas the opportunities and threats are from an external perspective. The strengths and opportunities are helpful in improving the situation, whereas the weaknesses and threats are to be considered harmful.

The *strenghts* of SoS research in Sweden relate to the broad basis:

- Many research organizations with some activities in the area.
- Many different research directions exist, which gives a ground for cross-disciplinary research.
- High competence in Software Engineering and Control Engineering, which is valuable also for SoS.
- High competence in empirical research methods, in particular in Software Engineering, which was one of the weakness identified in international research (see Section 3.1.3.3).

The *weaknesses* are caused by the distribution of resources and focus:

- Few researchers in each environment, research is very distributed and there is a lack of meeting places.
- Few researchers focus on the SoS area, but they merely touch it as part of some other research.
- Low academic competence in Systems Engineering, which is a key element of SoS.

The *opportunies* are:

- Much of the research is outside the government driven sector, and instead focus on commercial and innovation oriented systems, which provides a novelty compared to much of the international research.

- A highly relevant national industrial basis, both in the communication infrastructure which is an important enabler, and also in application areas such as automotive and transportation, automation, power systems, healthcare, and smart cities, which are increasingly addressing SoS. This provides the researchers with good possibilities to do empirical studies.
- A potential to create successful multi-disciplinary research environments, either within existing organizations or across multiple organizations.

The primary *threats* are:

- Lack of funding, especially for investigating core principles of SoS, and for performing border-crossing, interdisciplinary research.
- Still a low volume and very initial research, with a risk of even further losing ground to the international competition, in particular in the USA and EU.

3.2.3.3 Validity

As indicated in different places above, it is a challenging task to try to create a map of a research area such as SoS, and the root causes for these difficulties lie in definitions and delimitations. What exactly do we mean by SoS, and how narrowly should we interpret the subject? The narrower we are, the crisper and more comprehensive a picture can be drawn, but on the other hand, the risk of missing important actors increases. In this work, we have chosen to be fairly liberal and inclusive, and let the respondents in the surveys interpret the term SoS from their own perspective, based on only a high-level intuitive definition of the area. In this way, we have been able to identify at least some researchers who do normally not use the term SoS, but still do relevant work. Still, delimitations have to be made, and one such was to not consider all complex systems to be SoS, but only those where the constituent systems have an independence, as discussed in Chapter 2. The definitions and delimitations are thus a threat to validity, with the risk of both faulty inclusions and exclusions.

When talking directly to researchers, it is fairly easy for themselves to assess if they do research related to SoS or not. However, for funding agencies who deal with hundreds of projects and have to make the assessment based on short summaries of those projects, it is much more difficult to make an accurate judgment, and despite hard efforts by respondents at these agencies, the data is quite incomplete.

Some of the organizations have also given contradictory responses, where the central administration has answered that they do not have research in the area, but where researchers have nevertheless been identified who are clearly active. The opposite case also exists, where the administration say they do, but the indicated researchers do not agree. Partly, this is probably caused by misunderstandings of the concept of SoS, but overly positive replies could also reflect a fear of missing opportunities. Not being on the map of SoS research could mean that the organization would not be eligible for future funding, should some agency choose to expand in the area.

During the course of the project, there also appears to have been changes in some of the funding organizations. For example, the Knut and Alice Wallenberg foundation responded in December 2014 that they do not fund SoS research, but in late May 2015 they launched a major initiative to fund research in autonomous systems and software development by 1.8 billion SEK, and it would be surprising if that program did not involve any SoS related research. Also, SSF initially responded that they have not had any programs were SoS is explicitly targeted, but in April 2015 launched a 300 Million SEK program on Smart Systems, where SoS is mentioned as one of a handful of key areas.

The main strategy to overcome all these difficulties was the triangulation described above, and we believe that even though many details could be wrong or missing, the overall picture is probably fairly accurate.

3.2.4 Summary of Swedish research

Swedish SoS research is still in its infancy, but has started to grow in attention. There is a fair number of individuals involved, and even though it is hard to give a precise number, a reasonable estimation is between 50 and 100 senior researchers. However, most of these to not work exclusively on SoS, but most of them has touched the area while doing research on other topics. Many of them do not even call their research SoS, but use other terms, such as Cyber-Physical Systems (CPS), Software Ecosystems, or Internet of Things (IoT).

The researchers are spread over a large number of organizations, both universities and institutes, which means that the numbers in each organization is fairly low, often a single or a few individuals. Organizations that appear to gather a larger number of researchers, within different subfields of SoS, are Lund University, SICS, FOI, KTH, and Chalmers/Gothenburg University, but it is not necessarily the case that the individuals in different departments work together on SoS research.

Many of the researchers in SoS in Sweden come from a background in Software Engineering or Control Engineering, and this is in contrast with the international research, which has its basis in Systems Engineering. Unfortunately, that field is not well represented in Swedish academia, which is a weakness for successful SoS research.

The research topics studied in Sweden are partially the same as internationally, including modeling and simulation, interoperability, agent-based techniques, architecture, and communication. However, some areas are more pronounced in Sweden, probably due to the background in other disciplines, and this includes business aspects (in particular innovation and software ecosystems), control systems, governance, and IoT).

However, there is little research in Sweden on the underlying, fundamental principles of SoS engineering. This is likely to be a consequence of the funding strategies currently implemented, that reward application oriented research within singular domain, and neglect more fundamental studies that give benefit to many industries.

4 Research and innovation actions

Chapter summary. *The increasing interest in SoS is a consequence of the digitization of society, where the interconnection of systems can improve the efficiency of many operations, in part through automation. System integration is traditionally a Swedish area of strength, and by improving SoS knowledge, competitive advantages can be reached. SoS is also an important enabler for innovation, through the ability to combine existing technical products, processes, and organizations in new ways. Therefore,* ***Sweden needs a world-leading capability to rapidly develop trustworthy systems-of-systems****. This capability requires knowledge, competence, and capacity, which are provided through substantially increased research and education actions. The research should be driven by the SoS challenges related to theoretical foundations; socio-technical aspects; architecture; modeling and simulation; interoperability; trust; business and legal aspects; and processes and methods. It is suggested that research in the area is organized as a national center-of-centers that coordinate activities at different academic member organizations. This requires increased research funding, and also close collaboration with beneficiaries in industry and public sector. There is also an urgent need for education, primarily in the foundational disciplines of systems engineering and systems thinking, and then in SoS. It is proposed that the center-of-centers also takes responsibility for this, by developing joint courses in those disciplines, including on-line courses for practitioners, and PhD schools for industrial and academic doctoral students. To complement this, societal actions are needed to remove obstacles for building SoS, and enforcing standards. It is further necessary to create meeting places that can fuel the interactions between individuals and organizations interested in SoS, and this includes triple helix based flagship projects where new techniques and practices are put into practical use. It is also necessary to connect to other national and international initiatives, in particular within EU, which can contribute to the development of the SoS engineering capability in Sweden.*

In this chapter, it is presented what actions Sweden should take in the area of SoS, based on the analysis carried out in this project. The chapter starts with a summary of why the area is important, and then the desired capability is described. In Section 4.3, key topics that need to be improved are presented, and then the final sections of the chapter describe specific actions in research, education, by society through e.g. standardization, and by the creation of meeting places for creating and maintaining the interactions between different parties, which can lead to new innovations based on SoS. In the final subsection, related initiatives are discussed, including other strategic agendas, both in Sweden and internationally.

4.1 Importance of the area

One of the strongest driving forces in society today is digitization, and the opportunities and challenges this brings. Brynjolfsson and McAfee (2014) describes how it is possible to automate more and more systems that were previously considered to require human control and monitoring, and the consequences this automation brings. The automation is often used to streamline flow, and then it is rarely sufficient to automate a particular component, which is only responsible for one step in the flow. Instead, one must connect the automated components so that their work is coordinated, and this then often leads to an SoS. Knowledge on SoS is thus a prerequisite for improvements such as those aimed for in the reindustrialization (Industry 4.0). Much focus is however to date on the automation of components, and the integration of the whole is a neglected area of great potential. Not the least, there are good opportunities for innovation, where an independent operator or user may find new ways to integrate systems, and thereby create new services and features. Many of these innovations will be border crossing, since the SoS creates opportunities to connect systems that traditionally have not had anything to do with each other.

Different actors in society have begun to see the needs of SoS, as described in Section 2.4 above. In transportation, there is a strong trend towards communication between vehicles and with the road infrastructure. The solutions developed are, however, tailored for specific functions, reducing the possibility of rapid innovation. Production and logistics are also moving towards solutions where flows are optimized through the interconnection of systems. In society there are many functions, e.g. in crisis management and health care, that could benefit from SoS solutions for better resource utilization, shorter response times and higher quality. Within energy systems, so-called smart grids are being increasingly used, where the exchange of information between devices in the network enables better control and lower energy consumption, and in homes different systems are also interconnected. Generally, the development of solutions is however specific to individual companies or industries. For successful SoS development, solutions need to be open, but in a controlled way so that you can still control the security and intellectual property in order to gain trust in the system.

Systems integration is a traditional Swedish area of strength, and many successful Swedish companies such as Ericsson, Volvo, ABB and Saab, have been able to exploit this knowledge for a long time, previously often in cooperation with government agencies such as Televerket, Vägverket, Vattenfall, and FMV, even though this close industry-government cooperation has deteriorated in the last few decades. Possibly the Swedish culture, with a focus on collaboration and openness, is a reason for this. It provides a good basis for the integration of SoS, and the Swedish system-building industry can increase market shares by developing solutions that can be easily integrated into an SoS, and be able to offer integrated solutions in the form of systems and services. A Swedish home market gives an opportunity for these companies to develop such solutions, and the society benefits from rapid access to efficiency improvements that result from SoS integration. It also provides a breeding ground for SME's that can either help with specific components, or to specialize in the integration of SoS in specific areas to create special services. Finally, the innovations can also benefit society at large, including both industrial and societal activities. Ultimately, they contribute by increasing quality and efficiency, for both users and tax payers.

The importance of SoS to innovation cannot be overemphasized. As described in the Oslo Manual (OECD, 2005), innovation can occur as new products, new processes, or new organizational principles. Often, however, innovation is not the result of making new technical inventions, but rather combining existing technology in new ways, or combining existing products, processes and organizations differently. The combination of existing resources in new ways is the core value of SoS, and increasing the ability of SoS engineering can thus be expected to have large effects on the pace of innovation.

As stated above, SoS is an area with great potential, which is also highlighted by numerous analyses, and the importance will increase as digitization progresses. Meanwhile, current activities are fragmented, and are performed within individual sectors, which in many ways runs counter to the idea of SoS.

4.2 Desired capabilities

Given the importance of the area, and the challenges that remain in SoS engineering, as described in Chapter 2, it is essential for Sweden to increase its capability in developing SoS, both for the commercial industry and for responding to societal crises. More specifically, we argue that the objective should be the following:

Sweden needs a world-leading capability to rapidly develop trustworthy systems-of-systems

There are good reasons for focusing on the two aspects of rapidity, and trustworthiness. Being rapid is essential in the market place, where the first one to enter reaches a competitive advantage. It is a good enabler for innovation, which often involves trying new solutions in real life to assess their value, and seizing an opportunity when it arises. It is also essential for efficiently responding to a societal crisis, both military and civilian, where the time to assemble the necessary resources into an SoS is often decisive for the outcome of an operation.

Being trustworthy is also important. It means that we dare put SoS to work in situations where safety or security is a must, taking on tasks such as transport automation, healthcare, industry automation, etc. The risk of losses is reduced, with savings both in lives, and money. This also arises in the area of crisis response, where losses can be multiplied in effect if they lead to a failed operation.

However, rapidity and trustworthiness are often seen as conflicting qualities, since building trust traditionally requires elaborate verification and validation of every step in the development. Achieving the desired capability is therefore a considerable challenge.

It is clear that the most important resource for achieving this capability is *knowledge* and *competence*, where competence is the ability to get the job done, which requires knowledge but also many other things. Both these resources are essentially carried by people. However, there also has to be *capacity*, i.e., a sufficient number of people, since the need for SoS arises in many business segments and parts of society. There is thus a need for increasing education in the area, for engineers but also for managers and leaders. In specific areas, new technical solutions are required to provide efficient mechanisms for SoS integration.

Sweden as a nation is to some extent a developer of SoS, when it comes to systems in the public sector, including defense. The desired capability is thus important for those government agencies. However, as digitization progresses, it can be expected that industry will have an increasing need for SoS capability, and for Sweden as a nation, the role is then to provide education and research in order to provide a work force with sufficient knowledge, competence, and capacity to industry to make it possible for companies to conduct SoS development and operation here. This will surely have a large effect on the pace of innovation in the country. Society can also help by adapting policy and legislation that can hinder SoS deployment, and include interoperability requirements in system acquisitions.

Compared to many other countries, Sweden has a fairly strong basis in innovative SoS in the commercial sector, and this should be further emphasized. However, we are lagging behind when it comes to incident SoS, both for civilian and military applications. We should continue to build our strength for the innovative use of SoS, but not forget the ability for incident responses. The suggested capability is highly relevant in both cases.

4.3 Key research topics

To attain the capability to rapidly develop trustworthy SoS, knowledge has to be built in a number of areas, and these are to a large extent the same as were presented as SoS challenges in Section 2.5 above. Here, the topics will be summarized, and their importance from the perspective of the desired capability is highlighted. The topics need to be studied by researchers in order to increase knowledge, and also be treated as part of education to transfer the knowledge to practitioners. It is important to stress that the topics are highly interrelated, and need to be treated through cross-disciplinary research. Most of the topics are also applied in their nature, which means that the research should be carried out in close contact with practitioners in order to gather empirical evidence.

- *Theoretical foundations*. There is a need in general for a more advanced theoretical foundation for the SoS field, including a more precise language for describing and reasoning about SoS. Specific topics include emergence, which is currently not well understood, but is essential since creating an emergent behavior is usually the raison d’être for the SoS. The principles for the design of mechanisms that create the desired emergent behavior and properties is also a key topic which is in its infancy.
- *Socio-technical aspects*. Many of the SoS challenges in practice relate to the organizations that manage the SoS and its constituent systems, and the need for agreements and negotiations

between them. Finding efficient ways to deal with this is essential for rapid SoS development. Also, as automation progresses, a more fundamental understanding of the interplay between the technical systems and the people and organizations is needed, as the distribution of work between them changes.

- *Architecture*. Architecture is and will remain a central part of SoS engineering, and further refinement of methods for describing and evaluating the architecture is needed. In particular, the architecture is an enabler for rapid assembly of constituent systems into an SoS, simply because a good architecture will make the pieces fit better together, thus requiring less time for adjustments. It is also an enabler for trustworthiness, by describing clear principles and distribution of responsibilities between the constituent systems. There is also a need to focus on the architecture of systems that could become a constituent, and find ways of building flexibility into those systems from the beginning to make them adaptable to the needs of a future SoS, thereby reducing the duration of SoS integration.
- *Modeling and simulation*. Modeling involves describing the SoS in a simplified way, and has a strong relation to architecture. Capturing the essential structures and behavior in a concise way is an enabler for an efficient communication between the involved organizations, and thus leading to more rapid agreements. Many of the existing modeling frameworks can be improved, in particular there is a need for light-weight versions that can be used to rapidly capture the essentials. Models are also used as input to simulations, which allow for early verification of the emergent properties. In particular, co-simulations where existing models of constituent systems can be integrated are of importance, especially when complemented with efficient ways of visualizing the effects for decision makers. Modeling and simulation are thus a foundation for rapid SoS engineering, allowing fast iterations of design and evaluation. Their value in establishing trust, through extensive analysis of, e.g., safety, merits further research.
- *Interoperability*. To be able to link the constituent systems together, interoperability is a key. Techniques for achieving this exist, especially on the syntactic and to some extent semantic levels, but further development is needed to handle pragmatic and organizational interoperability. Achieving interoperability is largely founded on standards, which take a very long time to develop, and there is an urgent need of finding more flexible mechanisms that allow rapid achievement of interoperability, even between existing systems.
- *Trust*. There are multiple dimensions of trust that need to be handled, including dependability, robustness, security, and privacy. The particular aspects related to trust in SoS are caused by the operational and managerial independence of the constituent systems, and maintaining trust over the evolution. An overarching challenge lies in combining trust with rapid development. For this, new techniques need to be developed, and the most promising way forward is based on systems thinking, where progress is already being made in the safety area. This should be combined with simulation based approaches which allow rapid reevaluation of trust during system evolution.
- *Business and legal aspects*. Much of existing knowledge about SoS comes from government driven applications such as defense, and there is a lack of understanding of business models for commercially oriented applications. This includes also the design of mechanisms for keeping the SoS together, including both motivations and punishments for constituent systems. In many situations, legal contracts are needed, and to avoid lengthy negotiations, template contracts should be developed for rapid conclusion of the necessary agreements. There is also a lack of understanding of liability issues related to an SoS, when severe losses result from the emergent behavior of the SoS rather than from an individual constituent system.

- *Processes and methods*. Although many of the principles of general SE also apply to SoS as well, there are also fundamental differences. The SE processes are typically characterized by working top-down, and by tackling complexity through decomposition. The SoS processes need to be bottom-up and focusing on integration of existing element. To this should be added the need for speed, which is not one of the strengths of SE. There is a need for a better understanding in general of the SoS processes, and in particular how to efficiently organize cross-organizational development. In this, management and leadership aspects play important roles.

In Section 2.5, standardization was also mentioned as a challenge. This topic is however less related to research, and will be discussed separately in Section 4.6 below.

In the coming sections, concrete actions are presented, that are needed to reach the desired capability.

4.4 Research actions

As outlined in the previous section, there is a need for increased knowledge in many areas related to the rapid development of trustworthy SoS, which calls for a substantial increase in research activities. The SWOT analysis in Section 3.2 above gives a starting point for identifying the necessary actions. In summary, that analysis shows that there is broad research community in Sweden, but it is scattered in many places and with few people involved, giving a limited capacity and lack of focus, which is in part caused by the lack of funding for interdisciplinary and border-crossing research. There is a high competence in software and control engineering, and in empirical research methods, which is valuable for SoS research, but the lack of systems engineering competence is alarming.

The primary needs in relation to research to reach the desired capability are thus:

- Increased *capacity*, with more researchers that focus on SoS.
- Improved *cross-disciplinary collaboration*, to tackle the research challenges of the area.
- Improved knowledge in the foundational areas of *systems thinking and SE*.

To address these needs, the following actions are proposed:

- More *research funding* dedicated to SoS, also for research on the theoretical foundations and for generic research that is not directly tied to a specific sector in industry or society. Much of the current funding from Vinnova and other agencies are tied to a certain sector through strategic innovation programs and to specific societal challenges. An increased capability in SoS development would benefit all those programs, but it is hard to get funding to focus on SoS from any one of them.
- Creation of *coordinated research centers* for SoS, to enable cross-disciplinary collaboration with a critical mass. There are several research environments in Sweden that are increasing their activities in areas related to SoS, and the need for SoS capacity will be spread over the country. Therefore, it makes sense to scale up capacity at several places. The vision should thus not be a geographical center, but rather a *center-of-centers*, i.e., a joint national organization which co-ordinates activities carried out in existing research environments in a few different parts of the country. Similar centers exist in the US, but to our knowledge not in many other countries, and this action could thus give Sweden a unique position that allows us to very rapidly move to the forefront of the international research community. The topics presented in the previous section form an initial research plan for such an organization.
- Close *collaboration with beneficiaries* in industry and public agencies, in order to ensure relevance, and through research increase the knowledge and competence of practitioners. The natural research methods to use for SoS are empirical studies and design science, which both require a foundation in practice. To further strengthen the cross-organizational cooperation

within the center-of-centers, joint demonstration projects with industry or public sector should be used to drive the research, so that ideas can be tested in situations close to those encountered in real life.

4.5 Education actions

Research and education go hand in hand when it comes to building and transferring knowledge. The suggested increase in capacity for research will also provide a capacity for teaching. However, the need is not only for teaching of SoS engineering, but there is a large gap relating to the more fundamental disciplines of SE and systems thinking. A search[7] for courses dedicated to those areas at Swedish universities for the academic year 2015/16 revealed only one relevant course, in Systems Thinking at Linnaeus University. The urgent need for more engineers with a training in SE and other disciplines has been emphasized by industrial participants in the agenda project, and it is also necessary as a basis for recruiting new researchers to fill the capacity needs.

The primary need in relation to education to reach the desired capability is thus:

- Increase *education* in systems thinking, systems engineering, and SoS engineering at several universities in Sweden.

To address these needs, the following actions are proposed:

- *Develop courses* in systems thinking, systems engineering, and SoS engineering at the SoS center-of-centers. The participating universities in the center-of-centers should be obliged to provide such courses on a regular basis, both at the Master's level and for PhD students. However, the course material can be developed as a co-operation, thereby establishing a national curriculum in the area.
- *Provide on-line courses for practitioners.* Building the desired capability only through undergraduate education will be far too slow, since in most cases it takes many years of practical experience to achieve the necessary SE competence. An important complement is therefore to educate also practitioners in systems thinking, SE, and SoS. Luckily, modern technology for on-line distance education provides an excellent tool for this, and the SoS center-of-centers should provide a common platform for such education as well.
- *Provide industrial and academic PhD schools.* There is a need for research education to fill the capacity needs in SoS, but also to provide industry with advanced experts in the area. The center-of-centers should organize a national school for both industrial and academic PhD students, covering SE in general, but with a particular focus on SoS challenges.

4.6 Societal and standardization actions

To further fuel the advancement of SoS in Sweden, public authorities of different kinds can contribute in making SoS development easier, both in the private and public sector. One part of this is to routinely include requirements on open interfaces and interoperability when acquiring systems, thereby allowing them to become constituent systems of an SoS in the future. Important steps in this direction is already taken through the work of the eGovernment delegation. It includes also enforcing important standards related to system interfaces.

The government needs to act in different international organizations, to ensure harmonization of legislation that can hinder the creation of SoS for the international market. This includes a wide range

[7] The search was performed using the site antagning.se. The search was for individual courses. Possibly, there could be other courses that are only given as parts of a program, but it turned out to be difficult to search for those.

of issues, spanning from radio spectrums to variations in privacy legislations. The exact actions in different areas require a deeper analysis.

4.7 Interactions and meeting places

To further fuel the interactions between different actors within SoS, there is a need to create continuously active meeting places. Many of the issues in SoS go across different sectors of industry and society, and having such a meeting place provides a way of continuously building competence through interactions between academia and practitioners, and by creating new networks between individuals that enhances the capacity.

The ultimate goal of the interactions is to enable the creation of more and better SoS, and therefore there is also a need for larger initiatives by government and industry to create flagship projects through triple helix (industry, academia, government) collaborations. In such projects, new techniques and practices can be put into real use, thereby contributing to real value, but also to the establishment of de facto standards, and through the creation of evidence and knowledge about which SoS solutions work in practice.

A good foundation for this has already been created as part of this agenda project, but it must be ensured that this continues. Once a center-of-centers for SoS is in place, it becomes a natural role of that organization to provide such a meeting place, and in the meantime, voluntary efforts through organizations like INCOSE Sweden, and through further instances of the academic conference SWESoS, which was initiated as part of the agenda project, will play that role. It is also desirable to reach out to the international communities, and establish Sweden as a focal point in the SoS domain. One means of achieving this is to attract some of the major international conferences in the area to Sweden, and to invite leading international researchers here for shorter or longer collaboration visits.

4.8 Related initiatives and agendas

A number of initiatives already exist with a bearing on SoS engineering. For a start, Vinnova has initiated more than 130 strategic research and innovation agenda projects similar to this one during the last couple of years. Some of them explicitly mention SoS as a topic, and others are obviously related to SoS due to the challenges they present. Broadly speaking, there are two types of agendas in this set: one which describes the needs of a particular industry segment (e.g., the aircraft industry, transportation, medtech, electronics, mining, process automation, production, food, tourism, etc). Others are instead disciplinary, and describe challenges that go across a number of sectors in industry and society (e.g., material sciences, hydraulics, tribology, wireless communication, ICT, software, simulation, and Internet of things). This agenda for SoS is an example of the latter.

Some of the agendas have been the basis for strategic innovation programs, and several of these relate to SoS. This includes the programs on Automated transportation; Medtech 4 health; Innovair (aeronautics); Smarter electronic systems; Internet of things; Production 2030; and Process Industrial IT and Automation. In addition, the Vinnova program for Vehicular Research and Innovation (FFI) is relevant. In all these programs, there are effects to be gained by letting existing systems co-operate, thus essentially forming an SoS. Each of these programs would thus benefit from increased SoS capability in Sweden, and it should be expected that they also contribute to build knowledge in this subject.

On the European level, several research agendas related to cyber-physical systems and SoS have been produced. In particular, the Cyber-Physical System of Systems project[8] is worth mentioning. The project is a support action for exchanging information between related projects and organizations, and has produced some roadmaps on the area. The Cyber-Physical European Roadmap and Strategy project[9] is

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[8] http://www.cpsos.eu/
[9] http://www.cyphers.eu/

another project with similar goals, but for the CPS area in general. However, it mentions SoS as one of the key characteristics of future CPS. There has also been some European research projects in the area, including the DANSE project[10], focusing on designing for adaptability and evolution in SoS engineering by applying a model-based systems engineering approach with co-simulation and formal verification. AMADEOS[11] (Architecture for Multi-criticality Agile Dependable Evolutionary Open System-of-Systems) is another relevant project, which has a focus on architecture. All these efforts appear to be in line with the research directions suggested in this agenda.

It is worth noting that there are no Swedish partners in any of these European consortia, except for CyPhERS, where KTH is a partner. Leveraging on the ongoing and future SoS initiatives in EU is essential to improving the Swedish capability in the area. However, to become an attractive partners in these projects, it is necessary to first rise the national knowledge.

[10] http://www.danse-ip.eu
[11] http://amadeos-project.eu/

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6 Lists of participants

In the following appendix, individuals who have participated or contributed to the project are listed. (There have also been smaller contributions of a number of other people.)

6.1 Workshop participants

The following persons have participated in at least one of the four workshops organized by the project.

Name	Organization
Jonas Andersson	Decisionware AB
Romanas Ascila	Vattenfall
Jakob Axelsson	SICS - Swedish Inst. of Computer Science
Rolf Björkenvall	FMV
Lars-Ola Bligård	Chalmers University of Technology
Jan Bosch	Chalmers
Mathias Ekstedt	KTH
Ulrik Franke	FOI
Joakim Fröberg	SICS Västerås
Karin Garcia Ambrosiani	Syntell AB
Darek Haftor	Linnaeus University
Mikael Hagenbo	FHS
Martin Hagström	FOI
Niklas Hallberg	FOI
Rogardt Heldal	Chalmers
Erik Herzog	SAAB
Helena Holmström Olsson	Malmö University
Per Johannisson	Nii
Eilert Johansson	SICS Swedish ICT
Göran Jonsson	Volvo Cars
Daniel Karlsson	Volvo GTT
Kjell Lagerström	www.timevm.com
Harold Lawson	Lawson Konsult AB
Harald Lepp	FMV
Lars Löfgren	Försvarshögskolan / École Polytechnique
Konstantinos Manikas	University of Copenhagen
Karl-Arne Markström	ÅF Technology AB
Bengt A Mölleryd	IVA / KTH
Robert Nilsson	Volvo Car Group
Sebastian Näslund	ÅF Technology AB
Daniel Oskarsson	FOI
Patrizio Pelliccione	University of Gothenburg / Chalmers University
Afifa Rahatulain	SenseAir AB
Per Runeson	Lunds tekniska högskola
Gustav Sandberg	ÅF Technology
Johan Schubert	Innovationsgruppen
Peter Sjöberg	Volvo CE
Tom Strandberg	Syntell AB / INCOSE
Ingvar Wikström	Citan Consulting AB / INCOSE

6.2 Research survey participants

The following researchers and funding agency officials have provided information about the research they conduct or support.

Namn	Organisation
Samuel Fricker	BTH
Kai Petersen	BTH
Krzysztof Wnuk	BTH
Jan Bosch	Chalmers
Jonas Sjöberg	Chalmers
Tomas McKelvey	Chalmers
Bengt Lennartson	Chalmers
Sara Malmgren	Energimyndigheten
Lars Löfgren	FHS
Kristin Strömberg	FMV
Anders Berg	FMV
Niklas Hallberg	FOI
Martin Hagström	FOI
Fredrik Lantz	FOI
Anders Törne	FOI
Patrizio Pelliccione	GU
Per Andersson	HHS
Ulf Seigerroth	HIJ
Anne Persson	HIS
Mats Brommels	KI
Stefan Östholm	KKS
Elisabet Ohlsson	Knut och Alice Wallenbergs Stiftelse
Petter Ögren	KTH
Robert Lagerström	KTH
Svante Gunnarsson	LIU
Darek Haftor	LNU
Jerker Delsing	LTU
Thomas Gustafsson	LTU
Valeriy Vyatkin	LTU
Per Runeson	LU
Karl-Erik Årzen	LU
Paul Davidsson	MAH
Ulrik Eklund	MAH
Helena Holmström Olsson	MAH
Fredrik Bruhn	MDH
Mattias O'Nils	MIUN
Jakob Axelsson	SICS
Hans Liljenström	SLU
Olof Lindgren	SSF
Theo Kanter	SU
Jonas Bjarne	Vinnova
Tomas Andersson	VR
Jonas Jansson	VTI
Frans Prenkert	ÖRU