Systems of Systems Management and Governance from a Risk-Handling Perspective

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Abstract—**Managing a system can be critical for its successful functioning. This is especially crucial for the socio-technical systems of systems (SoS) that characterize many of modern society's critical operations. However, the management of SoS becomes complex as systems are increasingly interconnected and the dependence among connected systems intensifies. This paper explores the current state of the art on SoS management and governance from a risk management perspective. Our findings show a higher focus on SoS management; however, many studies do not holistically deal with the SoS. Moreover, our findings indicate fewer studies in SoS governance. Hence there is still a research gap. The study contributes to the body of knowledge by adding insight into how risk management fits in these domains and provides direction on the possible areas of mitigating risks.**

Index Terms—**Systems-of-Systems, Management, Governance, Risk management**

I. INTRODUCTION

Effective management seems necessary to achieve the desired outcomes for the systems of systems (SoS) that characterize modern society. These systems exist in key domains such as health, defense, energy, and aviation [1]–[3]. In aviation, an example of a SoS comprises independent systems for radar, ground maintenance, and in-flight, among others. Each system is managed independently, and systems work together to achieve a flight service. They form a network of interconnected systems that cooperate while operating independently to achieve a shared objective [2]. Failure to achieve such an objective often leads to a loss of service and even the loss of lives. Failures in SoS often result from the inability to manage integrated systems effectively. A SoS that is not well managed is likely to fail [1]. Hence, the management of these systems has become a major issue. Managers of these critical systems in society need effective approaches and tools to manage and govern them.

SoS management ensures compliance by organizing and executing necessary activities and facilitating resource sharing, methodologies, and tools sharing [4].

When an SoS is effectively managed it achieves the desired outcome: greater capability through enhanced efficiency and optimized resource utilization [2]. This increased capability emerges from the combined abilities of CS which form a system greater than the sum of the individual parts [5]. Thus, the integration of independently managed CS gives rise to a complex systems with unique characteristics, such as greater capability. The new SoS, like any other system, necessitates effective management and governance to achieve its objectives.

A. Current SoS Management

A new SoS needs to be viewed and managed holistically. However, recent research in SoS shows that current management methods and tools to support effective system management have been based on individual systems [4]- [6]. These management approaches therefore lack the holistic view that is necessary for complex systems.

Additionally, [3] observed that management methods and tools for SoS are few or incomplete. Moreover, [6] argues that current risk analysis and SoS management, designed for different domains, are ineffective in addressing the characteristics of SoS in their current form. They further point out that these management approaches are based on project management and centralized planning, which assume that future states are known and that there is one controlling manager. The latter implies a static view of the systems, whereas SoS are dynamic. Thus, there is a need for more research on SoS management because current approaches overlook the holistic perspective, address static systems, and the tools are inadequate.

B. Purpose of Study

This paper presents a literature review to examine recent research on SoS management and governance, specifically focusing on their link with risk management, in particular risk of SoS not meeting its common objective. The purpose of the literature review is to present a current state of the art on SoS management and governance from the perspective of risk management. This will provide an updated overview of SoS and governance. To achieve this objective the paper explores the following research questions:

- RQ1. What is the recent research focus and narrative about risk, management, and governance within complex SoS?
- RQ2. What approaches are proposed and in what domain?

C. Overview of Paper

The remainder of the paper is structured as follows: In Section II , we present the background and theory, and Section III outlines the analysis methods used. In Section IV, we report on the literature review. We end with a discussion and conclusion in Sections V and VI, respectively.

II. BACKGROUND AND THEORY

The background and theory of this study lay the foundation by outlining key concepts crucial to understanding the scope and objectives of the research. Among these fundamental concepts are SoS, risk, SoS management, and governance. SoS, in its essence, represents interconnected systems forming a larger, more complex system that has more capabilities than the individual systems. Understanding the intricacies of risk within SoS contexts is paramount, as it involves identifying and mitigating potential threats and uncertainties across interconnected systems. These potential threats and uncertainties create the risk of SoS not meeting its common objective.

Furthermore, the section examines the domain of SoS management, exploring existing methodologies and frameworks for effective complex systems such as SoS. Thus, the section provides a foundation for a thorough investigation of the dynamics of SoS management and governance within the framework of the research.

A. Systems of Systems

SoS comprise people, organizations, and technology artifacts termed constituent systems (CS) that are separately designed and managed independently. These CS cooperate and join into larger, dynamic complex systems called the SoS. [2]. Boardman and Sauser [6] proposed the following characteristics as features of SoS:

1) Autonomous: CS in SoS have managerial and operational independence.
2) Belonging: Systems in SoS can choose to belong to SoS depending on their needs.
3) Connectivity: The CS are capable of interfacing with and linking to other systems within the SoS.
4) Diversity: Systems are heterogeneous.
5) Emergent: New properties emerge because of SoS evolution.

The main objectives of such a cooperation are to achieve greater capability through emerging behavior for a common objective and to provide effective and efficient service at a lower cost of operation. With these objectives, SoS has increasingly been used in critical domains of society such as health, transport, and defense. Collaboration among systems aims to enhance capability and provide efficient service, preventing property and life loss.

One way to ensure a greater capability of achieving SoS objectives is through risk management in the SoS and incorporating tools and a management approach to ensure the SoS is well managed.

Researchers [4], [6], [7] agree that coordinating different activities to efficiently use resources, which are roles of management, lowers costs, improves quality, and achieves desired results.

B. Definition of SoS Management

In the SoS literature, several different types of management are discussed. Each of these types of SoS is differentiated by aspects relating to decision power and control. The most common archetypes of SoS are called directed, collaborative, and virtual [3], [8]. In directed SoS, there is an influential CS, a keystone that acts as the key element whose main function is to tie the whole system together by fostering consistency, integration, and stability among the many subsystems. A keystone is a central actor sending commands to independent CS as it performs its key function. In contrast, in a collaborative archetype with no keystone, the CS interact voluntarily to fulfill an agreed purpose. Organizations owning the CS decide how to provide or deny service. On the other hand, for virtual, there is no central management concept and a lack of agreed SoS purpose.

C. Principles and Definition of SoS Governance

SoS governance is a multidimensional concept related to a more strategic vision, containing regulations, policies, requirements, best practices, and decision-making criteria to guide the SoS toward the achievement of its objectives [9]. [10] agrees with this thought and defines SoS governance as a collection of guidelines or rules, directives, and standards for decision-making that direct the SoS toward accomplishing its objectives. Another definition by [10] refers to SoS governance as a holistic view of equilibrium for direction and order. Thus, the terms SoS governance refer to the control, direction, and responsibility of decision-making within a regulatory framework of the systems being managed.

D. Risk Management

Effective SoS management is concerned with managing risk, hence risk management is a core element in managing SoS [5] [11]. This is because risk assessment directs the process of choosing options, authorizing procedures, and implementing risk-reducing measures [12]. This reduces the risk of failure. The risk of failure within a SoS can stem from various sources. Firstly, risks may originate from individual CS, as problems within one CS can cascade and affect the entire SoS. Additionally, risks may arise from the inherent characteristics of SoS, such as emergent behaviors, evolutionary changes, and the overall complexity of the interconnected systems [13].

Given these multifaceted risks, effective risk assessment becomes paramount for the management and governance of SoS. Unlike traditional risk assessments tailored for single systems with clearly defined boundaries, SoS risk assessments must encompass a broader scope. Traditional assessments often overlook interconnections between systems and focus solely on risks impacting individual systems. Consequently, the tools and methodologies commonly used for traditional risk assessment may prove inadequate when applied to SoS contexts.

E. Traditional Tools

Traditional CS tools mainly include project management activities for planning [6]. These tools address integrated systems or are based on other domains. In a literature review [4], 74 percent of the studies indicated no tools for SoS management; an additional 8 described tools from other domains. This underscores the need for tools that support the management of SoS and their characteristics.

F. Emerging Trends from SoS Management Literature

A variety of tools have been suggested as management strategies for SoS. These include approaches and frameworks, such as the value-at-risk (CVaR) approach to SoS risk management, that support analytical techniques for SoS-level decision-making [13]. The techniques look at operational risk, cost, and capability to find the best possible system portfolios. It entails integrating observable data and simulation methods into the decision-making process. The system dynamics (SD) model [14] presents a system management framework for disaster recovery that makes use of system dynamics to improve decision-making in complex systems.

Following the presentation of the study's background, this paper proceeds to highlight the methodology used in this study.

III. METHODOLOGY

This study adopts a qualitative design, using a literature review methodology, to gather data on SoS management and governance studies. It follows the guidelines provided by [15] and [16], which advocate a thorough analysis of primary research to ascertain the existing body of evidence on a specific matter. The guidelines also advocate a literature review to be carried out through a process of organizing or planning, executing the plan, and reporting.

A. Background: Initial Literature Review

A literature review was conducted to explore the challenges and complexities associated with managing a SoS during the COVID-19 pandemic in Sweden [17]. Articles were evaluated based on their relevance to COVID-19 management in Sweden and their potential contributions to understanding SoS dynamics. From the initial 151 studies, 24 articles were selected, while 13 studies that were unrelated to SoS in Sweden were excluded [17]. Interestingly, it was observed that many of the excluded papers had a common theme: the general management of SoS. Consequently, a secondary literature review was undertaken to specifically focus on these excluded papers. This study is the secondary literature review, examining 13 primary studies.

B. Organizing Data for the Review

Data used in this review was initially excluded from our primary review described in Section III-A. The aim was to identify any insights and emerging themes related to SoS in general that could enrich the understanding of the research topic and to answer the research questions in Section I-B. The studies constitute our primary data source in this paper.

Therefore reviewing this data set allowed for the discovery of new themes and insights about state of art on SoS management and governance.

Thus the review forms a qualitative study that analyzes the literature on SoS management, risk management, and governance.

C. Search

The review has an identified common theme with keywords SoS management, risk management, and governance in their variations and returns the primary documents. The search strategy remained consistent with the initial review conducted on multiple data sets, including the databases Scopus, Google Scholar, Science Direct, and Springer.

In this review, we selected thirteen papers as primary studies, which were initially excluded in the initial study, from the review process.

D. Screening

Research studies that had the keywords:" risk management"," systems of systems," or "SoS governance" were incorporated into the study and were selected for data extraction. Of the primary papers chosen for this study, 10 studies met the inclusion criteria and were selected for the data extraction stage.

E. Data Extraction

Following the inclusion of studies, the data extraction criteria were formulated using the research questions, namely:

1) What is the focus of the study?
2) What are the keywords?

IV. DATA ANALYSIS AND REPORTING

This section provides an overview of the findings and themes identified in the literature on SoS management. The results are summarized and then synthesized for insights from various selected studies in the field of SoS management. Table 1 shows more studies with a focus on SoS management than on governance. Using a data extraction criterion the study examined several recent studies on a range of SoS management topics, particularly risk, management, and SoS governance. A detailed examination of ten selected papers makes it evident that the majority of the reviewed literature is focused on these subjects. This highlights the topic's importance in navigating the complexities of SoS. The topics' narratives from the reviewed literature are outlined in the remainder of this section.

TABLE I
DISTRIBUTION OF STUDIES TO TOPICS

Topic		
Management	*Risk*	*Governance*
[18] [19] [20] [21] [22]	[23] [24]	[9] [25]

A. Narratives on SoS Management

The narratives about SoS management cover a wide range of research emphasizing risk management including adaptation, transformation, and trust primarily in crisis management systems.

The study [18] uses crisis management as an SoS. It studies the SoS management challenge of the difficulty of building and sustaining these capacities in a coordinated and economical manner. Consequently, the authors present a model for adaptation and transformation when managing crisis management systems. This model combines general systems theory and organizational learning theories. By introducing effectiveness as a performance metric for evaluating crisis management systems and their subsystems, the authors propose a model to improve comprehension of learning and change dynamics.

In [19], Alauddin et al. examine risk management for both traditional systems and SoS, using the complexity of SoS as justification for the need for more quantitative approaches. A model-based strategy is put forth that lessens dependency on arbitrary data and encourages comprehensive risk management. It uses Monte Carlo techniques. Additionally, the study by [20] investigated how risk perception and risk management are influenced by the media and public trust in risk management organizations. Researchers looked at the contradictory relationship between institutional trust and risk perception, determining whether or not people's desire to personally manage risk is positively or negatively correlated with their level of trust in risk management organizations.

Research on crisis management [26] discusses the development of distributed cognition and crisis management capabilities post-2015 MERS-CoV, using the South Korea case, offering practical implications for managing future COVID-19 waves and public health crises.

Furthermore, Chen et al. [21] discuss inadequate reserves and the lack of coordinated efforts to allocate the available resources to the designated area. The paper proposes a three-pillar framework for resource planning and allocation, inspired by classical risk aggregation and capital allocation theory, offering policymakers insights for informed decision-making, although potential improvements and limitations are acknowledged.

Asharaf draws attention to multi-hazard management, highlighting that disasters are increasingly happening simultaneously [22]. He discusses the integrated response and highlights how existing systems, such as flood early warning systems, were successful. He highlights an example of communicating the COVID-19 danger in countries like Nepal and others. He advocates integrated disaster management policy, addressing challenges such as preparedness, trade-offs, vulnerable group susceptibility, and cooperation with civil society and frontline workers. He further calls for new holistic methods to manage disasters.

B. Narratives Focusing on Risk

Klucka et al. [23] recommend mitigation strategies based on unknown hazards, which include societal concerns, political and economic instability, a lack of knowledge and experience, and other dangers. They systematically and spontaneously detect problems and threats. The measures have to be examined and contrasted with other metrics to determine their growth and efficacy. The framework that the identified dangers generate for execution is aimed at a comprehensive approach to risk management.

In the study by [24] Stafford Beer's Viable System Model (VSM), which is based on the law of requisite variety, provides a framework for the investigation into what structural requirements are both sufficient and essential for organizational sustainability. These requirements are developed using regulatory systems, which include executive management, coordination, basic operations, auditing, strategic management, and normative management.

The narratives on SoS management are being studied from a broad spectrum of perspectives. These include adaptation, trust and communication, and resource management. For example, studies such as [18] propose models for enhancing dynamics and effectiveness. Additionally, [20] explores media and public trust while approaching management from a capability perspective.

C. Narratives on SoS Governance

The review found that governance aspects were researched by [9] and [25]. Katina et al. [9] argue that SoSE focuses on the coordination and integration of systems, enabling greater capabilities than the sum of the constituent systems. However, there is a lack of qualitative studies on coordination and integration. They proposed complex system governance as a basis for improving system-of-system performance.

Zahariadis et al. [25] focused on policy and trust highlighting the politicization of professional advice. They examine how different policy philosophies and political trust levels affect crisis management responses across national borders

D. Comparisons of Narratives

The narratives on SoS management encompass various research themes, including risk management, adaptation, transformation, trust, and communication These studies address challenges such as building and sustaining capacities in a coordinated manner during crises [18], the complexity of SoS necessitating quantitative risk management approaches [20], and the influence of media and public trust on risk perception and management. Additional practical implications for managing crises, such as COVID-19, are discussed in studies like [26], which examines distributed cognition and crisis management capabilities post-MERS-CoV. A resource planning and allocation framework and integrated responses to advanced was proposed by [21], [22].

Furthermore, a focus on risk management includes recommendations for mitigation strategies based on various hazards [23] and the application of Stafford Beer's Viable System Model for organizational sustainability [24].

These narratives provide insights into the multifaceted aspects of managing, mitigating risks, and governing SoS,

offering frameworks and models to enhance effectiveness and resilience.

V. DISCUSSION

Existing management approaches lack a holistic approach for complex systems such as SoS. Further, the United States Department of Defense (DoD) guide [27] observes that 'Risk management is a core function of systems engineering at all levels'. Thus, managing risk in an individual system does not mean managing risk in the SoS. To properly handle risks in an SoS, it is not enough to just handle risks separately for each CS. Additionally, current risk analysis and SoS management tools are ineffective as they are mostly based on project management and centralized planning, which assume a static view of the future states of the system [4]- [6]. Hence, there is a research gap in the approaches, and in an understanding of SoS management and governance. This literature review focused on management, governance, and their connection to risk management, providing an overview of research progress in addressing existing research gaps.

We explore the various SoS themes that emerge from the literature review's narratives and outline their significance.

Most studies [18]–[23], [26] in the review have a prominent focus on various SoS management aspects related to risk management. However, there are fewer studies [9], [25] on SoS governance.

Therefore, the review shows a significant emphasis on risk management aspects in SoS management and a notable research gap in SoS governance. The themes identified from the review are discussed in the following subsections.

A. Themes from Narratives

Several themes emerged from the narrative of the literature on SoS governance and management.

1) Complexity of SoS Management: SoS are complex due to their dynamic nature and interconnected parts [2]. Hence, managing an SoS is equally inherently complex and calls for coordinated efforts along with adaptive strategies to mitigate risks from various sources. A study by Pettersson et al. [28] found that an evolving SoS has challenges and complexities from different sources, such as collaboration, capabilities, and management. Hence, research needs to incorporate broad aspects of risk approaches to mitigate such complexities and challenges.

2) Mitigation Strategies for Risk: Another theme emerging from the review is the implementation of mitigation strategies for risks. An example, [26] advances that in SoS crisis management readiness and reaction skills may be strengthened by putting into practice mitigation measures that take into account unforeseen risks, such as public trust and political instability. Some studies [18] propose approaches for managing risks in the SoS such as quantitative risk management techniques, such as the Monte Carlo method and Bayesian belief networks, to improve the accuracy and scope of risk assessment in SoS. In essence, the mitigation of risk through different approaches

contributes to risk management. In this literature review risk management is widely discussed.

It follows therefore that risk management is an integral part of SoS management.

3) SoS Governance: SoS governance, like SoS management, is discussed from different perspectives. These include policy, trust, and engineering governance [9], [25].

B. Significance of Results

The review shows the management of risk that can contribute to the efficiency of SoS has a higher focus. This illustrates the importance it holds in the domain of SoS. However, further data analysis shows that only a minor portion of the examined publications explore SoS administration and governance. This indicates a research gap and suggests more study in the fields of SoS governance and management. The implication is that the trends in research are yet to move toward a holistic approach to SoS management. This holistic approach is critical. The study by Pettersson et al. [28] found that SoS management faces various challenges as the SoS evolves.

For the SoS to achieve its goal, for example, collaboration during emerging new risks amid new structures as well as issues of governance and policy will become a challenge if not addressed [17]. The authors of [18] indicates that the challenges of leadership for a collaborative development process and the roles involved were limitations for the implementation of their proposed framework. This is supported by a study by Pettersson et al. that found that unclear roles posed a challenge in the SoS for a wildfire rescue operation [28]. This implies that research in SoS management needs to incorporate broad aspects of risk approaches on SoS management that mitigate the complexities and challenges of SoS. Further, the need to mitigate a wide range of risks to include SoS management strategies can be seen in the results of research on the COVID-19 pandemic in Sweden and wildfire SoS operations [17], [28]. In [28] the study found that unclear responsibilities and roles are part of the characteristics of risk in wildfire SoS rescue operations. This implies that effective SoS management strategies should be part of risk management.

Further [17] found that inadequate policies and legislation during the evolution of an SoS are part of the challenges that create risk, indicating that adaptation to changing risks and complexity requires integrating SoS management and governance into risk management approaches. Therefore, inadequate consideration of governance and SoS management could hinder a holistic approach to risk management in SoS, and on improving SoS capabilities. This is the vital direction for advancing the field of SoS risk management.

For practice, policymakers should prioritize the development of comprehensive governance frameworks that foster coordination and integration across diverse stakeholders within SoS. Incorporating system governance into systems engineering will ensure best practices and enhance efficiency.

VI. CONCLUSIONS

This study examines the state of the art in SoS governance and management from a risk management standpoint. The

majority of the reviewed literature in this study focused on risk management, in which several approaches to risk analysis and management of SoS are outlined. While the importance of such research is acknowledged, there is still a need for studies to focus on SoS management and governance. We argue that risk management should be integrated into SoS management and governance. This integration is critical for comprehensive risk assessment and management to enable holistic mitigation of risks within SoS. This is demonstrated by real-world scenarios such as wildfire and pandemic response in Sweden, where clear responsibilities, governance policies, and structures were necessary for effective SoS performance.

Thus, this study examines the state of the art in SoS governance and management from a risk perspective. Insufficient understanding of the complexity of SoS governance and administration might prevent thorough risk assessment and mitigation strategies. Even if risk management is still crucial to understanding and minimizing risks within SoS, the interdependence, and complexity of SoS require an extensive approach that includes governance and management of the entire SoS in addition to risk.

A. Future Work and Study Limitation

Future research should focus on SoS management processes to address existing literature gaps and contribute to knowledge. Prioritizing research on tools and processes can help organizations navigate complexities and enhance resilience. The limitation of this study is that the papers were limited within a shorter time frame, and research could be underway on risk management and governance.

VII. Acknowledgment

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