Risk Analysis for System of Systems Management: The Swedish COVID-19 Management Case

Marjorie Nawila Pettersson
Computer Science and Software Engineering
Mälardalen University
Västerås, Sweden
marjorie.pettersson@mdu.se

Jakob Axelsson
Computer Science and Software Engineering
Mälardalen University
Västerås, Sweden
jakob.axelsson@mdu.se

Anna Johansson
Economy and Political Science
Mälardalen University
Västerås, Sweden
anna.johansson@mdu.se

Pontus Svenson
RISE Research Institutes of Sweden
Kista, Sweden
pontus.svenson@ri.se

2024 IEEE International Systems Conference (SysCon) | 979-8-3503-5880-3/24/$31.00 ©2024 IEEE | DOI: 10.1109/SysCon61195.2024.10553576

***Abstract*—A socio-technical system of systems (SoS) is a collaboration of independently operated and managed systems. These constituent systems join the SoS to work together for a common goal: to achieve positive emergent behaviors such as greater capability, efficiency, resource utilization, reliability, and robustness. To achieve such a goal, an SoS needs to be well-managed with mitigation plans for all system risks. However, existing risk management strategies were developed for individual, non-integrated systems and are therefore inadequate for use with SoS. This paper uses the COVID-19 pandemic in Sweden as a case study for exploring risk analysis for SoS management. We performed a risk analysis of this SoS based on STAMP (System-Theoretical Accident Model and Processes), an existing method from the safety domain, as part of developing a preliminary risk analysis process for practitioners. Preliminary results reveal that extended SoS structures, uncertainty-driven decision-making, emerging behavior, and changes in trust, policy, and legislation pose significant challenges. The study's contribution is that our findings provide a knowledge base to act as a guide for risk management of SoS. Applying a method for safety analysis to crisis management also extends the body of knowledge on methods for SoS risk analysis.**

Keywords—SoS Management, Risk Management, Risk Analysis, COVID-19, Crisis Management

I. Introduction

Systems of systems (SoS), which are collaborations of systems called constituent systems (CS), have increasingly been used in critical domains of society such as health, transport, defense, and crisis management. CS, separately designed and managed independently, cooperate and join into a larger dynamic complex system [1]. The new system, the SoS, is a complex sociotechnical structure that combines social and technical components to achieve shared objectives, with optimal performance and efficiency resulting from a harmonious connection between these components [2]. A CS joins the SoS to achieve a common goal and for the need to use positive emergent behaviors such as greater capability.

SoS are of different types called archetypes and these can be differentiated based on decision power and control [3]. The archetypes are categorized as directed, collaborative, and virtual. A directed SoS has a keystone, i.e., a central actor controlling operations, while a collaborative SoS has no keystone and organizations that decide service provision. On the other hand, a virtual SoS completely lacks a central management concept [3]. Regardless of the type of SoS, the main objective of CS cooperation is to achieve greater capability through emergent behavior for a common objective and to provide effective and efficient service at a lower cost of operation.

For an SoS to achieve its objectives, it should be well managed. However, it has been pointed out that the rapid growth of SoS in society has not matched the corresponding knowledge on managing these systems, leaving gaps in research on responsibility and roles in complex SoS [2]. Thus, it is suggested that risk management strategies meant for individual static systems are applied to an SoS; however, an SoS is dynamic, and its structures are not fixed with predefined roles and responsibilities.

In a previous study [4], we found that unclear roles and responsibilities were among the risk characteristics in a wildfire SoS operation. Hence investigating the characteristics of responsibility from the perspective of SoS management provides an opportunity to observe how responsibility and roles play out as SoS evolves.

In its simplest form, management is getting things done through available resources, which can include people, material resources, and information. The concept of management is best understood from a resource-based perspective and that of managers, i.e., those who undertake the task of management, are responsible for obtaining integrating, and directing diverse resources to fulfill an organization's objective [5]. Management, however, needs an approach for it to be effective and efficient, and in general, such approaches include planning and decision-making, organizing, leading, and controlling [6].

Management of a system becomes complex when organizations that need to be managed are SoS because they consist of interconnected systems. Difficulties related to management can occur from various dimensions. For example, [7] observed that multi-organizational crisis responder networks frequently underperform or even disintegrate because of challenges in achieving effective coordination, information sharing, and collective decision-making, which are elements of management. Thus, the management of SoS is more challenging due to its complexity, which arises from the dynamic nature of SoS and its emergent behavior.

Additionally, the management of SoS is challenging in that, in the SoS, each CS retains its managerial and operational independence while still aiming to achieve the objective of the SoS [1]. The preceding challenges illustrate the need to explore how the SoS should be better managed. Additionally, the dynamic nature of SoS makes it necessary to have a continuous approach to risk analysis and management [8].

This study utilized STAMP, modified for SoS [8], for risk analysis in investigating COVID-19 management. STAMP emphasizes safety as a dynamic control problem based on system component linkages. Further, to learn more about SoS management, the study analyzed this Swedish complex crisis case as an SoS to identify potential challenges.

A. Case Study: COVID-19 Management in Sweden

The coronavirus SARS-Cov2, a virus that causes respiratory illness, appeared on the world scene at the end of 2019 and created a global health crisis that lasted until 2022. The pandemic significantly impacted people's health and economic and social well-being globally. There was large collaboration globally and in different countries to limit the spread of the virus. Different countries worldwide responded by implementing various strategies and measures, including the lockdown of entire cities and countries. The pandemic, an unprecedented event in human history, has also provided many research opportunities [9].

Sweden is one of the countries that did not implement a countrywide lockdown. Much has been written about Sweden's approach, and thus it is a good study case. The case study is used to explore existing research gaps in SoS management, namely that knowledge on managing risk in SoS is yet to be developed [2]. As a result, management methods and risk reduction strategies developed for individual systems and inadequate for SoS are used.

B. Research Questions

The paper addresses the following research questions:

1. What are the key complexities and challenges of managing an SoS, specifically in the context of the COVID-19 pandemic in Sweden?
2. How can SoS management be strengthened and improved using the lessons discovered from the risk management analysis employed in our study of the SoS COVID-19 crisis in Sweden?

C. Overview of Paper

The remainder of the paper is structured as follows: In Section II, we present the background and theory, followed by the analysis methods used in this study. In Section IV, we present the risk analysis performed using STAMP. We follow up with a discussion of the preliminary results and finish with the conclusion.

II. Background and Theory

Other studies undertaken on SoS management include [10]. This study proposes to view SoS as a network that can be governed by already established network management principles of fault, configuration, accounting, performance, and security (FCAPS).

Another view was presented by [11] where decision points and artifacts are used. It points out that SoS teams typically identify critical decision points and support them with diverse types of data, evidence, or knowledge that are frequently found in significant work outputs or artifacts.

Further [11] proposed a wave model of the SoS, a way that work outputs on artifacts such as developing architecture and system analysis can be done in SoS. However, the study does not focus on the management of the SoS but on the formal acquisition processes which are not always used to manage SoS evolution.

Nevertheless, [11] provides an insight into how a process in the evolving system could be done, and its application could be useful in the management of SoS. [6] points out that traditional management competencies include command and control and a focus on individual tasks; on the other hand, a standard procedure for new competencies includes being an enabler, empowering collaboration, and innovation.

Thus, as mentioned at the onset, a gap still exists in knowledge and tools to achieve these new competencies in the management of SoS. In addressing approaches to SoS management, [2] observes little evidence of the use or creation of practical management tools that support SoS management except for the use of one or two existing general management tools.

As researchers explore the effective management of SoS, it can be argued that effective SoS management without an analysis of risk would be inadequate. This is because risk management is crucial in formulating strategies to mitigate crisis impacts and maintain efficiency, reliability, security, and safety [8].

However, existing risk management practices applied to SoS are insufficient, as observed by [12], who concluded that the existing approaches and support tools for risk management at the SoS level are not yet well established.

To better understand risk in SoS management we explore challenges and complexities during COVID-19 crisis management operations in Sweden as an SoS. Additionally using the STAMP approach, modified for SoS risk analysis [8], we explore actions and interactions between system components and controllers and perform risk analysis on the SoS.

III. Methods

To conduct our case study in a structured way with a framework and background that appropriately positions our new research, we chose to start with a systematic literature review. A collection of scientific articles written on COVID-19 formed the data set for this study. The scope was the papers with content on Sweden, and the review primarily focused on the COVID-19 pandemic management operation as an SoS. The review activities are based on and adapted from the guidelines as outlined by [13]. The aim was to identify the narrative of the pandemic management that answered the research questions. Another methodology used in this study is a thematic analysis [14] outlined in Section II.D of this paper. Finally, to analyze the risk in our case study, we used STAMP, as described in Section IV.A-D.

A. Data Search and Selection

The databases Scopus, Springer, Science Direct, and Google Scholar were searched using a query for papers that discuss risk management, crisis management, risk analysis, and COVID-19. The studies were narrowed to those describing the situation in Sweden. Duplicates were eliminated in the study selection process. The search for papers was concluded in mid-July 2023. The selected papers were imported into Covidence, a research screening tool for study selection and further screening.

B. Procedure for Study Selection

Two levels of screening were conducted, namely, screening at the abstract level and full-text screening. At the abstract screening level, each abstract for a paper was read to determine if they discussed what was set out in the search criteria, namely risk management, systems of systems, crisis management, risk analysis, and COVID-19. During full-text screening, each entire paper was read in detail.

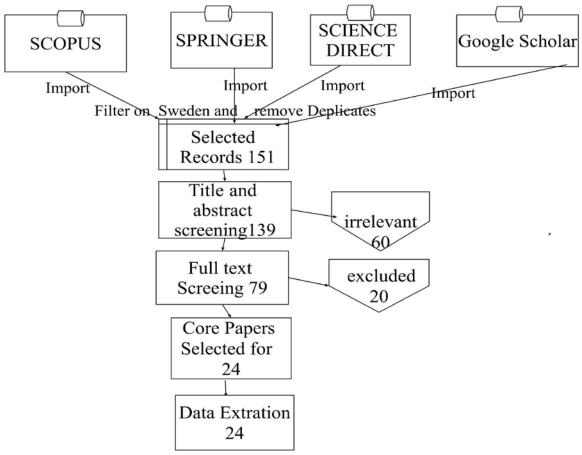

Fig. 1. Paper Selection Process.

Papers were excluded during full-text screening on the following grounds:

- Papers about internal matters in a single organization and not about societal crisis management.
- Lack of relevant information that answers the research questions.
- Discussion about the risk of disease, not societal risks.

The paper was included if it is written in English or Swedish, has content about the management of COVID-19 in Sweden, and also discusses any of the following:

- Risk management
- Systems of systems
- Crisis management
- Risk analysis

Fig. 1 shows the process leading to the extraction stage.

C. Procedure for Data Extraction

The final stage in the data collection process was the extraction of data using an extraction protocol based on research questions.

The selected documents from the data collection process were imported into NVivo because this research tool provided more functionality for analysis.

D. Thematic Data Analysis

The data in NVivo were thematically analyzed using an approach suggested in [14]. The procedure is as follows:

Data Familiarization: The study research tools Covidence and NVivo were used for paper review and coding. In Covidence, the abstracts from the papers were read, and then a full-text review was done. This was followed by coding in Nvivo.

Coding: Codes were created that target answering the research questions, using the following steps:

- *Search for themes:* Pattern grouping codes were identified.
- *Themes review:* A review of themes to determine what they represent was done.
- *Themes analysis:* We analyzed how the themes addressed research questions by categorizing the codes.
- *Findings:* The results from the thematic analysis were recorded.

Examples of codes created include:

- Approaches and strategies for COVID-19 management.
- Actions taken to manage the pandemic.
- Challenges in managing the pandemic.
- Actors in the management of the pandemic.

E. Results of Thematic Data Analysis

Twenty-four papers were selected as part of the study to understand the management of SoS and how it can be improved. The papers are drawn from various perspectives and areas of research that include policy, governance, health care, and economics. All papers provide a narrative and analysis of the approach Sweden took to manage the pandemic crisis. To understand the management of the Swedish pandemic, our research included exploring the challenges of SoS management. For the challenges and complexities of SoS, the thematic analysis indicated the following results:

- *Evolving environment*: The management of the pandemic had to deal with different scenarios of the pandemic or pandemic phases. The so-called "peak," or periods when a new viral variation emerged, or periods when a large number of people became infected, were some of the characteristics that defined the pandemic phases [15].
- *Changing management structures* These were actions to cater for emerging temporal healthcare facilities and new organizational structures [16].
- *Uncertainty: There was much uncertainty*, such as about what variants of the virus are already affecting the population, their severity, and the arrival timeline of upcoming vaccines [17].
- *Losses*: Mitigation of disease, death, and economic challenges.
- *Collaboration:* Strategies or actions for SoS management between different actors in the system [18].
- *Other factors*: Those affecting management related to trust, policy, and legislation [19].

To further understand how such challenges can be mitigated in the SoS management of the COVID-19 pandemic, a risk analysis was performed using data from the themes and applying the STAMP method, described in the next section.

IV. STAMP

In this section, the concept and components of the STAMP approach are explained. The section also provides an overview of the steps involved in applying STAMP to the case study in this study for SoS risk analysis.

A. *Overview of the STAMP Approach*

STAMP is a theory or set of presumptions regarding the nature of accidents. Its methods are used to investigate accidents and their causes in the safety domain. STAMP was created to deal with increasingly complex systems and emphasizes the role of control to find deeper causes of accidents and system failures [20]. The model explains unsafe interactions and accidents involving system components, complex software, human behavior, errors in design, and insufficient requirements [20]. It does this by adopting a holistic system-based approach, analyzing how interconnected system components and their interactions contribute to accidents or system failures. Thus, the system-based approach prioritizes comprehending the relationships, interactions, and interdependence within a system as opposed to concentrating only on its separate components [21].

In STAMP, safety is viewed as a dynamic control problem and a system problem [21]. It examines possible failures at different system levels, and therefore a hierarchical control structure is used to analyze the cause of accidents based on the actions of the actors involved. The main idea behind this structure is to create models of complicated system behavior among people in charge of risk management and to formulate system constraints or conditions that must be met by the system to avoid failures and accidents [20].

STAMP emphasizes interconnections between system components. This makes it a suitable approach to use in our study of the management of COVID-19 as an SoS. Moreover, the COVID-19 administration in Sweden was a social-technical SoS made up of components that collaborated to control the pandemic.

In STAMP, the two tools STPA (System Theoretic Process Analysis) and CAST (Causal Analysis based on Systems Theory) are widely used [20]. To remove or control hazards, STPA is a proactive analysis method that examines the possible causes of accidents throughout development, whereas CAST is a method for analyzing accidents in retrospect, thus analyzing past causes of accidents [20].

The objective of our research is to develop methods that can be used to identify potential risks in an SoS. This is also the purpose of STPA, and hence we use that method in this study.

B. *Modeling in STAMP Approach*

The components of STAMP as illustrated in Fig. 2 show a system that includes controllers, actions, processes, and feedback in a loop, which are defined as follows [20]:

- *Controllers:* In STAMP, a controller is a crucial system component or mechanism that regulates system behavior to maintain safety, ensuring the system functions within predetermined safety parameters.
- *Control actions:* Precise procedures or modifications carried out inside a system in response to any dangers or departures from safety parameters to preserve or restore it to a safe state. Thus, these actions are based on the feedback from the system and aim to prevent hazards.
- *Controlled process:* The activity, process, or system being managed or controlled by the controller.

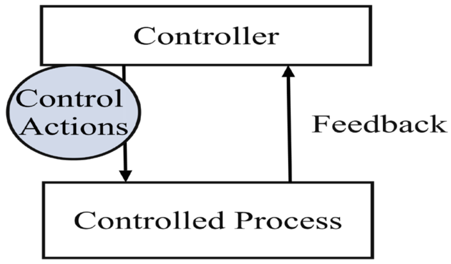

Fig. 2. STAMP generic hierarchical loop [20].

- *Feedback:* This is any information about the controlled process behavior during operations that is transmitted to the controllers.

Additional important concepts in STAMP are losses and hazards. A loss is something that should be avoided, for example, deaths or injuries. A hazardous state is a system state that, in the worst case, could lead to a loss. When STAMP is used in modeling to analyze actions and feedback for analyzing risk sources, hazards can be controlled or eliminated in a controlled process. This is done by finding the control actions that could cause the system to enter a hazardous state. These control actions are referred to as *uncertain control actions*. The final component of the STPA process is to identify *loss scenarios*, i.e., scenarios of the environment and incidents that could cause an uncertain control action.

Thus, in this study, the risk analysis for the case study will proceed as illustrated in Fig. 3 below with steps A to D, the steps adopted from [20]:

Step A: Define the purpose of the analysis.
Step B: Build a model based on existing data.
Step C: Identifying unsafe control actions,
Step D: Identify loss scenarios.

In the following section, STAMP is applied to information extracted from journal and conference articles to perform risk analysis and modeling of the COVID-19 case study.

A. *Purpose of Analysis*

In the risk analysis for the case study, the purpose of the analysis as outlined for the STAMP approach in [20][21] involves determining the system boundary by defining the system of interest (SoI) [22]. Outside the boundary of the SoI is the environment over which risk analysis has no control. The purpose of analysis also includes identifying losses, hazards, and constraints relating to the SoI in the system.

When applied to the COVID-19 SoS case study the purpose of the analysis is outlined as follows:

a) System of Interest: The system of interest [22] in the procedure for STAMP is the system under consideration. Thus, this study's system of interest under analysis includes all systems and activities related to managing the COVID-19

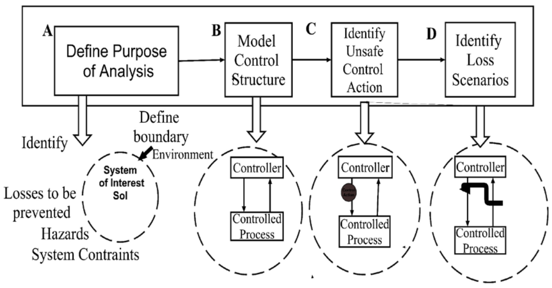

Fig. 3. Steps for risk analysis under the STAMP - STPA.

pandemic in Sweden. The SoI has system actors such as the central government, government agencies (including pharmaceuticals), regions, municipalities, private caregivers, hospital staff, and the public.

b) Losses: This refers to events that must be avoided or minimized. They are unplanned and undesirable. During the COVID-19 pandemic in Sweden, the following losses could be identified:

L1: Loss of life. The elderly living in care facilities, dealing with a variety of medical conditions if exposed to the virus and became ill, could die.

L2: Sickness. People become very sick and have long-term effects if they contract the virus.

L3: *Economic losses*. People contract the virus and become very sick and unable to work.

L4: Loss of trained healthcare workforce. Healthcare workers working in healthcare facilities contract the virus, become sick, and even die if not fully protected.

These losses are only a sample of what has been itemized by researchers.

c) Hazards: Hazards are a set of conditions or a system state, that when combined with environmental conditions could lead to an accident or loss. A hazard causes the loss of something of value.

Elements that have characteristics of risk in the system become hazards. Hazards therefore are system-level states or conditions that will cause a loss to occur [20]. In the SoS for the management of the COVID-19 pandemic, the following hazards could be derived:

H1: The system exposes the elderly to the virus [L1].

H2: The system has no mechanism for preventing the virus from spreading among the population [L2-L4].

H3: The system does not enforce guidelines for protection against the virus spread [L1-L2].

H4: The system does not have adequate protection for the healthcare workforce [L1-L4].

Hazards can be refined further as in the example below of hazard H1 in the SoS risk analysis. To prevent the system from reaching the H1 state, what can cause hazards is further analyzed and a sub-hazard example is derived following the STAMP approach as illustrated below:

H1: The system exposes the elderly to the virus [L1]:

H1.1: Protection is insufficient at points of contact between the elderly and those who may carry the virus.

d) System Constraint. System constraints are specified conditions that need to be met to prevent a loss or accident. The STAMP approach [20] states the procedure for determining the constraints as follows:

<System-level Constraint> = <System> & <Condition to Enforce> & <Link to Hazards>

The STAMP procedure above allows us to derive a system constraint that prevents the system from reaching a hazardous state. The SoS constraints could be derived as follows:

C1: The system must protect the elderly in care facilities from being exposed to the virus.

C1.1: The system must implement protection measures at the point of contact with the elderly.

C2: The system must protect the population from contracting the virus.

C3: The system must provide economic relief for very sick people during the pandemic.

C4: The system must adequately protect health workers.

The rest of the analysis section will create and discuss model structures for the COVID-19 crisis management SoS.

B. Modeling the System

In this study, the control structure illustrated in Fig. 4 has the main controlled process as the management of the COVID-19 pandemic or the process for the prevention of patients or the public from contracting the virus. Based on data from the research journals analyzed through our thematic analysis presented in Section III, sub-processes, feedback loops, and control actions were identified and included. The resulting model of the Swedish COVID-19 management system at the start of the pandemic is presented in Fig. 4. It was found that this structure changed during the pandemic.

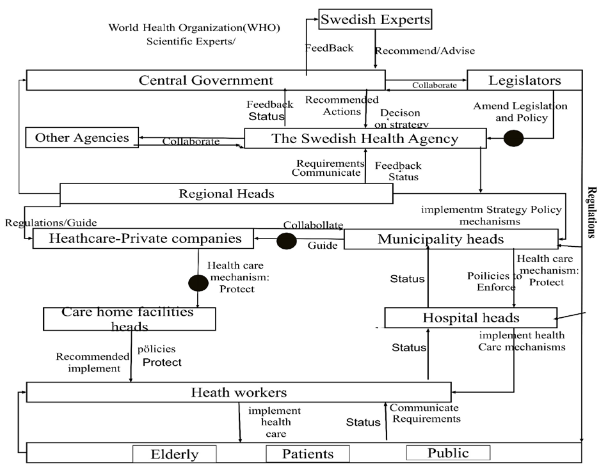

Fig. 4 Control structure for the first phase of the pandemic with a focus on the process for elderly care

Therefore, in this study risk analysis, the STAMP step for modeling the control structure is adjusted to include additional control structures at different points in time as illustrated in Fig.5.

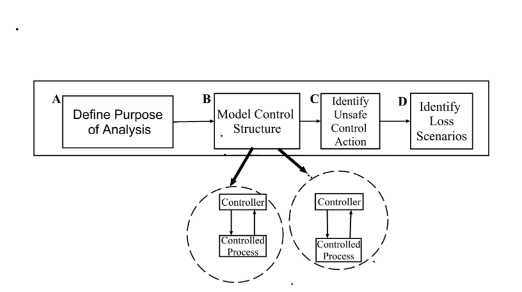

Fig. 5. Analysis adjusted to SoS.

Additional structures are created based on different periods of the system analyzed; for example, the model as the system evolved into the second phase of the pandemic is illustrated in Fig. 6.

Control actions relating to elderly care facilities are shown in downward arrows, and black dots show where control actions become unsafe if the control action is not applied. In particular, the unsafe actions illustrated in Fig. 7 relate to the process shown as a gray box in Fig. 6.

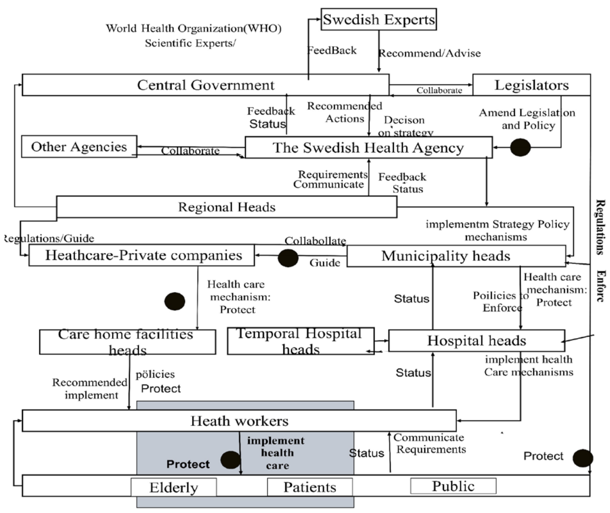

Fig.6. Second Phase of pandemic, Focus on the elderly care process.

Additionally additional structures such as a temporal hospital are visible in this phase.

Having done the models, the next step in STAMP is to identify unsafe control actions.

C. *What to mitigate: Unsafe Control actions (UCA)*

STAMP offers a methodical way to distinguish unsafe control actions (UCA) from the above actors' behaviors. The purpose of this study's analysis is to investigate how the management of the pandemic is conducted throughout the existence of the COVID-19 SoS and what barriers can become risks to effective management. Unsafe control action in this risk analysis indicates what to mitigate.

The table in Fig. 8 illustrates an example of how unsafe actions are derived. The procedure used is based on the STAMP model:

Identified Action along with UCA				
Control Action	***Not providing cause Hazard***	***Provided but Causes Hazard***	***Provided too early, too late, or out of order or sequence***	***Stopped too soon, applied too long***
Protect the elderly from exposure to the virus	Protection of the elderly. Measures such as requiring masks for staff and visitors in care homes. [UCA1]	Inadequate protection: Such as masks provided to caregivers but limiting visits to care homes by people without masks not done. [UCA2]	Protection of the elderly is provided too late when most elderly in care homes are infected. [UCA3] [UCA1]	N/A

Fig.7. Examples of Unsafe control Actions (UCA) from the SoS.

UCA1: The controller must introduce and update policies that ensure there are adequate mechanisms and policies for the protection against exposure of the elderly in healthcare homes.

Not providing causes: elderly are exposed.

Providing but causes hazard: if the policies are inadequate, they will cause more damage than utility.

Provided too early/late/out of sequence: too late causes the elderly to be exposed; too early causes resources to be wasted.

UCA2: The controller must add and update measures that the system can do to prevent the virus from spreading among the population.

Not providing causes: elderly are exposed.

Providing but causes hazard: if the measures are inappropriate or insufficient, they will cause more damage.

Too early/late/out of sequence: too late causes the elderly to be exposed; too early or out of sequence causes resources to be wasted.

UCA3: The controller must enable the system to take measures that slow the pandemic's spread.

Not providing causes: elderly are exposed.

Providing but causes hazard: Insufficient protection at points of contact for staff and the public causes more infections in care homes.

UCA4: The controller must ensure that the system has resources for health workers that match the demand of health workers' resource needs.

Not providing causes: elderly are exposed.

Provided but causes a waste of resources.

Too late/early: waste of resources, for example, if temporal hospitals are built but not used.

D. *Loss Scenarios*

The last step in the STPA process is to identify loss scenarios under which such uncontrolled action would occur. For the case under study, the study identified the following examples of loss scenarios.

a) Scenario where UCA1 occurred: Not providing: the controller is not aware of the pandemic and fails to implement correct policies. Providing but causes loss: the controller chooses an incorrect policy. *Providing too early/late: slow processes or over-eager controllers get the* *timing wrong*. There is inadequate protection from COVID-19 for the elderly in care homes.

b) Scenario where UCA2 occurred: Not providing: the controller is not aware of the pandemic and fails to implement correct policies; Mechanisms to control the virus spread are weak or unclear. Providing too early/late: unclear mechanisms led to failure to provide protection in time and the virus spreads.

c) Scenario where UCA3 occurred: Not providing: the controller is not aware of the pandemic and fails to implement correct policies; Measures to prevent the spread of the virus are not enforced. Providing too early/late: slow processes led to failure to provide protection in time.

d) Scenario where UCA4 occurred: Not providing: the controller is not aware of the emergency; there are no processes implemented to acquire the needed resources. Providing causes Hazard: resources are sent to the wrong locations. Too early/late/out of sequence: the processes for acquiring and allocating resources are too slow or get the wrong input.

V. Discussion

The background to this study is that literature reveals gaps in SoS management; the rapid growth of knowledge on the growing systems of systems has not matched the knowledge gaps for managing SoS [2]. Processes for SoS risk management are yet to be fully developed [2], so current processes and methods for SoS management are based on static systems, whereas SoS are dynamic systems.

Efficient management practice of systems starts with identifying risk analysis as a core activity [23]. Therefore, to understand SoS management, this study also undertook to explore risk analysis for SoS. The study aimed to identify and understand the challenges using Sweden's management of the COVID-19 pandemic as an SoS as well as perform a risk analysis on that SoS. Data was extracted from 24 studies presented in scientific journals and two key types of analysis, namely first, a thematic analysis for exploring complexities and challenges of SoS management and second, a risk analysis, were performed on the data. The thematic analysis addressed the initial research question, focusing on the complexities and challenges of managing an SoS in Sweden during the COVID-19 pandemic. The results from the thematic analysis are outlined in Section III.E and discussed in the following section.

A. Complexity and Challenges of SoS Management

When left unresolved, elements with risky features in the system become hazards and can pose a significant danger during the evolution of the SoS [3]. This is validated by our finding that fragmented structures posed challenges in the evolution of the COVID-19 SoS in Sweden. Information from the data sources for this study [14], indicates that in a normal situation, the challenge of fragmented structure had long been identified and recorded as a potential risk. However, these fragmented structures become a system flaw for management during the SoS evolution as stated by [16] [17] who point out that a 'number of flaws, including fragmented organization due to many actors with unclear responsibilities, a lack of common information technology systems' were among the challenges of management COVID-19 in Sweden. In particular [19] cites fragmented structures as a reason for COVID-19 management challenges for long-term care homes.

A lesson from this finding is the need for continued implementation and review of risk management mitigation strategies. For SoS this points to a need for reliant and adaptable aligned structures of management

Another result of this study was the challenge of making management decisions in a dynamic system environment. This agrees with arguments from [18] that in an uncertain environment decision makers struggle with incomplete information. Managing and making decisions in a dynamic uncertainty environment thus implies that decisions in SoS are even more complex.

One case is the emerging phases of the pandemic in Sweden. [19] points out that managing COVID-19 is one of Sweden's challenges that emphasizes the need for planning and policy under severe stress in extremely complex decision-making structures implying diverse and often unclear rules or guidelines.

Another case in point was the administration of vaccines. Decisions regarding the distribution of vaccines among other factors depended on supplies [21][18] with new events in the process of supply affecting the availability of the vaccines. Consequently, such uncertainty affected decision-making. [19] agrees by citing the Commission of Inquiry listing decisions surrounding vaccine distribution as one of the challenges of Sweden's management of COVID-19.

Furthermore, the Swedish principle of responsibility [24] where regions and individuals have the obligation to make decisions, implied that the SoS had no absolute central authority, and each constituent could make decisions that they saw fit regarding vaccine distribution as well as other operations in their region [25]. The direction of the entire SoS may not be harmonious. For the practice, such a challenge in the SoS calls for a balance of centralized control and decentralized control.

Having discussed what this study found to be the complexities and challenges of the SoS in the management of COVID-19, the following subsection discusses the risk analysis performed on the SoS using STAMP, addressing the second research question above.

B. Application of STAMP

The existing risk analysis method STAMP was applied to our research data as described in Section IV. To capture actions and risks in the dynamic SoS, the use of STAMP was modified to include additional control structures. This risk analysis provided additional insight into how challenges or risks arose as the Swedish COVID-19 SoS evolved and how potential mitigation strategies can be derived for the SoS system.

Among the risks emerging in the first phase of the pandemic were inadequate protection of the elderly in care homes, inadequate legislation to protect the elderly, health workers, and the public, and management during COVID-19. Worth noting also is that the risks already known in the system became larger with the evolution of the SoS. A lesson that could be learned is to address systemic risks in individual systems as they appear.

To summarize this discussion: The study reveals managing fragmented, extended structures, and uncertainty in Sweden's COVID-19 system posed a challenge, necessitating the implementation of risk management strategies and adaptable structures. Additional challenges were that decision-making and adapting legislation became complex in a dynamic system environment and required adaptable structures. The study also highlights the need for preparedness, managing extended structures, and balancing existing and new regulations to maintain trust and effectively communicate changes. Finally, the study underscores the need for continuous risk management.

VI. Conclusion and Future Work

This paper presents the results of a study to understand the challenges and complexities of crisis management in a system of systems. The case under study was the management of COVID-19 in Sweden. Preliminary results indicate that decision-making in a dynamic SoS, managing extended structures, and dealing with emerging risks are among the challenges. We also presented scenarios of risk by applying the safety analysis method STAMP to the operations of the COVID-19 crisis SoS.

Our contribution is to provide knowledge that can serve as a base and guide for SoS management and risk analysis. Using an existing method for analysis, this study provides a practical example of the use of STAMP modified to address the dynamic nature of SoS as procedures based on static structures are no longer effective when done on a dynamic structure. The results suggest how new risk management procedures for SoS can be derived for risk analysis related to SoS management.

This study focused on a case in Sweden and hence there is a possibility that some of its findings will not apply globally owing to varying social and political influences. It would therefore be interesting to replicate the study on cases where the circumstances are different.

Future work also includes applying the process of risk management of this study to more examples of SoS in different domains and then formulating a process for SoS risk management and analysis.

Acknowledgment

This study was funded by the Swedish Civil Contingencies Agency (MSB) under grant no. 2021-13694.

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