Towards a Risk Analysis Method for Systems of Systems: A Case Study on Wildfire Rescue Operations

Marjorie Nawila Pettersson
Mälardalen University
marjorie.pettersson@mdu.se

Jakob Axelsson
Mälardalen University
jakob.axelsson@mdu.se

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

Anna Johansson
Mälardalen University
anna.johansson@mdu.se

ABSTRACT

Crisis management (CM) is facing new challenges due to the increasing complexity of contemporary society. To mitigate a crisis, it is often necessary for a collection of independent systems, people, and organizations to cooperate. These collaborating entities constitute an interconnected socio-technical system of systems (SoS). An important question is how a CM SoS should be constructed to minimize the risk of failure and accurately handle a crisis. SoS pose new challenges in analysing risk during interactions. This paper investigates whether the risk analysis method STAMP (System-Theoretic Accident Model and Processes) is suitable for SoS, using a forest fire rescue operation case study. Results show characteristics of various risk sources and identify some SoS characteristics, such as dynamic structure and latent risks, that are not sufficiently handled in STAMP. The study further contributes to the body of knowledge by presenting potential directions for research on SoS risk assessment methods.

Keywords

Systems of systems, risk analysis methods, case study, wildfire, STAMP. Crisis management

INTRODUCTION

Crisis management in the twenty-first century is more challenging than before because the operations have become more complex to handle. For example, due to climate change, crisis management operations are now more complex, often requiring input from numerous people, systems, and organizations. These crisis responders are socio-technical systems of independent elements that collaborate, thus forming systems of systems (SoS) whose activities are key to resolving the crisis. The collaboration is driven by communication, and the SoS can thus be seen as an information system (Benali and Ghomari,2016).

A crisis is an abnormal or extraordinary event or situation that threatens an organization or community and requires a strategic, adaptive, and timely response to preserve its sustainability and integrity (ISO 22361:2022). As pointed out by Khodarahmi (2009), the purpose of CM is to tackle a particular crisis as efficiently and quickly as possible. However, as the crisis gets bigger, so does the SoS needed to handle it. The "numbers involved, the various levels of the social structure that they represent, the heterogeneous mix of public and private organizations involved, and so forth, virtually assure the impossibility of achieving total overall coordination during the emergency period" (Quarantelli, 1988, p. 383).

Additionally, such CM SoS come with their own risks. The more systems get connected into an SoS and become dependent on each other, the more the number of risk sources increases. Moreover, each element in an SoS has different priorities and views of situations. For example, in a fire rescue operation, the immediate priority of spontaneous volunteers (SVs), such as landowners, was to use all means available to save assets. Trained firefighting organizations, on the other hand, approached the operations with safety as a priority. Persson & Uhnoo (2021) point out that these situations create dilemmas that occur because professionals work in organizations and

situations where professionals must consider multiple and potentially conflicting institutional logics.

The SoS complexity underscores the need for supporting tools and ways to handle crisis management of risk as crises get more complex. Methods to assess and mitigate this risk during the interaction of these interconnected systems have been a subject of discussion in literature (Lopes et al., 2020; Rasmussen,1997; Siu,1994) where there is a call for better and more holistic methods of risk analysis.

This study is a preliminary component of research on developing a process for risk analysis in SoS, to contribute to the body of knowledge of SoS methods by presenting potential directions for research.

One way to achieve holistic SoS risk analysis is to propose improvements to existing methods or build new holistic methods based on existing ones. Evaluation of such existing methods for effective use of risk assessment in SoS is a necessary step in this process. The methods must be able to deal with the complexity of SoS and address all possible sources of risk.

The sources of risk that emerge during the activities of the interconnected systems in an SoS and the methods of assessing such risks are of interest in this paper. In evaluating the usefulness of an existing risk analysis method in isolating these sources of risks, we model the behaviour of the different entities involved in the crisis response as an SoS and seek ways of doing qualitative and quantitative risks analysis and, later, optimization of the crisis response in the context of SoS.

Research Question and Approach

This study addresses the following *question: What characteristics during the interaction between different interconnected systems (the CS of the SoS) become sources of risk?*

The study applied STAMP (Leveson, 2004), as a tool to identify SoS risk characteristics and to evaluate the method's ability to handle holistically SoS risks, to investigate whether the risk analysis method is suitable for SoS.

STAMP has been used in our study because it is based on system theory, and it has been increasingly employed for safety analysis in recent years. STAMP is also assumed to be useful in extremely complex systems including socio-technical systems (Leveson et al., 2003).

In Sweden, in 2014, one of the first real complex CM was due to a forest fire. Forest fire outbreaks are increasingly common and getting larger, often ending in a crisis. They often require the collaboration of various elements of independent organizations, such as meteorological organizations, firefighters, transport agencies, and volunteer groups (Prakashav et al., 2021). Together, they provide a good example of an SoS. Collaboration is mainly achieved through information exchange, and many risks are the result of failure in this communication.

In this paper we applied the STAMP method to the risk analysis of the fire rescue operation as a preliminary approach to creating a risk management process.

Overview of Paper

The rest of this paper is organized as follows: In the next section, we discuss the background, focusing on STAMP and SoS. We then consider related works, followed by a description of the case study and an outline of the methodology used. This is followed by an analysis of data from the case study and a discussion of the preliminary results. We end by summarizing the conclusions of the paper and providing some directions for future research.

BACKGROUND

This section provides a brief overview of the STAMP method and the SoS concept.

The STAMP Method

The STAMP approach is used to investigate accidents and their causes. It consists of systems-theoretic process analysis (STPA) and causal analysis (CAST) as two analysis methods. STAMP is based on systems theory, which was developed after World War II to cope with increasingly complex systems arising from advanced technology (Leveson, et al., 1998, 2003).

STAMP employs a hierarchical control structure, with the key idea being to use the structure in formulating

constraints for system controllers and building models of complex system behaviour among those responsible for managing risk.

STAMP advances that accidents can also be caused by unsafe interactions between system components (Leveson and Thomas, 2018) and that these unsafe interactions cause accidents because they violate system constraints. Hence, in STAMP, safety is treated as a dynamic problem through feedback loops of information and control (Leveson, 2004).

Leveson et al. advocate that the benefits of STAMP are that more complex systems can be analysed, and the method ensures that the hazard analysis includes all potential causal factors present in the system model.

To assess STAMP's applicability for risk analysis for SoS, our study applied it to a fire rescue operation case.

The SoS Concept

A system of systems (SoS) is a set of systems or system elements called constituent systems (CS) that interact to provide a unique capability that none of the constituent systems can accomplish on its own (ISO/IEC/IEEE 21839:2019, p. 2). A SoS brings about emergent capabilities that an individual organization is not able to possess. Additionally, the SoS can achieve more efficiency, better quality, and better utilization of resources at a lower cost. This is primarily the result of communication, and the SoS can be seen as a loosely coupled information system.

The SoS concept is linked to systems thinking in engineering, where a key relationship is between the system (the whole) and its elements or parts and where the elements interact with each other (Axelsson & Kobetski, 2018). As they interact, these elements exhibit certain characteristics, outlined below.

Characteristics of SoS

The characteristics that set SoS apart from integrated systems are as outlined by Boardman and Sauser (2006):

1. *Autonomy:* CS have managerial and operational independence.
2. *Belonging:* CS joins an SoS based on a cost-benefit analysis of their own system and the SoS.
3. *Connectivity:* CS can link to other systems.
4. *Diversity:* CS have unlike elements in a group, and
5. *Emergence:* The appearance of new properties during the course of development creates the emergent capability needed to achieve the goal of the SoS

Along with these characteristics, the different CS have various capabilities that, when combined during system interactions, result in the creation of a new and powerful SoS capabilities. "In many cases, systems were not originally designed for a particular SoS, may support multiple SoS for multiple missions, and are owned and operated by an independent organization with their own goals and objectives" (Dahmann, 2013). An important consideration, therefore, is how risk in such a diverse environment can be isolated and mitigated.

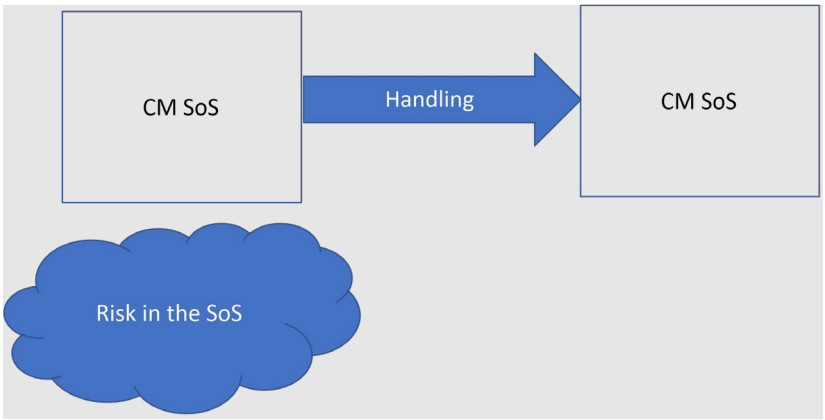

Figure 1: Risk emerges during a fire rescue operation

A crisis response effort such as the selected wildfire rescue operation case is an example of an SoS when we consider the above characteristics. As more fires have occurred in recent years, fire rescue operations have become complex. This means that there is a greater risk that some of the CS of the wildfire management SoS can fail, and there is thus a need to design the SoS so that it is resilient.

The CS of the wildfire rescue SoS includes ground, air, and space vehicles, ranging from bulldozers and fire engines to helicopters, fire-monitoring air vehicles, and earth observation satellites, that exchange information. Often, these vast systems are operated by separate agencies and are therefore managerially independent and evolve their capabilities on their own. (Prakashav et al., 2021). Such an operation is illustrated in Figure 1.

The brief consideration above of the STAMP method and SoS concept led us to consider related work,

RELATED WORK

In this section, we provide a broad overview of risk and proceed to highlight two of the categories or views from which risk has been discussed in the literature. The works reviewed are related to our study in that they each aim at providing a method for risk analysis.

Our objective is to perform risk assessment in an interconnected system of systems, to identify possible sources of risk during system interaction, and to better understand the shortcomings of existing methods.

We reviewed work on methods for individual system components as well as methods for integrated systems. This puts us in a better position to select a suitable existing model and approach as the basis for a method of assessing risk in SoS.

Risk is often expressed in terms of risk sources, likelihood, potential events, and consequences; thus, risk is traditionally defined as the effect of uncertainty on objectives (ISO 31000:2018). This effect is negative, such as a loss of value to stakeholders, and the uncertainty is the likelihood of the event happening, such as a fire operation's failure to suppress a wildfire.

Different methods exist for the assessment and management of such risks. These methods are often static, focusing on the known system boundary. It cannot be assumed that these risk methods applied to individual systems would automatically work for SoS (Kinder et al., 2017).

Thus, as society and systems become interconnected, it has been argued over time that the traditional methods are insufficient for risk analysis of the interconnected systems, in particular for SoS, because often risk analysis is focused on individual systems (Shah et al., 2015; Baumgart et al., 2017).

Earlier Methods Based on System Thinking

A unique aspect of systems thinking is that the system is looked at as a whole rather than as a collection of separate

parts. Additionally, system thinking is concerned with properties that emerge when parts interact, and these arise from relationships between the parts of the system (Arnold & Wade, 2015). The relationship between the system and its parts creates a hierarchy.

Based on this system-thinking approach, Rasmussen (1997) studied the concept of socio-technical systems, which involve multiple societal levels of control mechanisms. He argued that instead of focusing on sequences and events derived from human errors, a model of behaviour shaping mechanisms in terms of system constraints should be used (Rasmussen 1997).

Rasmussen further pointed out that "numerous research models and methods have been useful in analysing and managing risks in individual systems," however, "they are not very useful for analysing the performance of the total risk management system" (Rasmussen, 1997, p. 184).

Rasmussen's study formed the basis of the Risk Management Framework (RMF) a model for accident causation and safety controls. RMF was accompanied by Accimap, a generic framework for listing and identifying contributing factors across various levels in socio-technical systems (Salmon et al., 2012).

The approaches of Rasmussen (1997) and Salmon et al. (2012) on risks in socio-technical systems are of interest to this study because socio-technical systems are what make up the SoS. While the methods proposed by these researchers were a shift from traditional risk management, they remain static in their approaches concerning the structure of the SoS.

Leveson (2004) extended Rasmussen's concept by developing a modeling framework, STAMP. As discussed earlier in this paper, the STAMP model recommends that organizations establish objectives, requirements, and constraints to mitigate risk. STAMP views safety as a hierarchical organization in which to control the behaviour of the individual components and the interactions among the system components, controllers are determined throughout the hierarchy. These provide control actions on the system and get feedback to determine the impact of the control actions (Leveson and Thomas, 2018). To maintain safety within determined boundaries, control structures trigger assessment and re-assessment of a situation.

Based on systems thinking, the system under risk assessment has emergent properties that emerge when components interact, and these emergent properties develop from the relationship among components. STAMP has been widely used in risk assessment. However, the method has an equally static approach. The lack of rigor and flexibility has been pointed out as a shortfall in the method (Axelsson, 2020b).

Methods of SoS Risks

Aitken et al. (2010) proposed an approach using the fault tree technique; the model focuses on communication within the SoS. The gap in that study is that it is a risk model for the static configuration of an SoS. As a result, Aitken et al. point to future research as the need to apply the model to dynamic SoS problems to broaden the technique.

Gandhi et al. (2012) argued that in the traditional approach to risk management (focused on managing risks for CS), there is a tendency to analyse risks in individual system components without considering the holistic view of interactions between the potential risks at the CS level and their consequences for the SoS. They, therefore, proposed a systematic risk approach that looks at risk from a perspective originating from many sources. They suggest that systemic risk can be thought of as the risk or probability of breakdowns affecting an entire system and not just a breakdown in individual parts or components, as evidenced by correlations among most or all parts.

Pinto et al. (2012) approached risk management across sectors of society by deriving a set of questions for risk management in SoS. The proposal was that these could be used as a guide and included questions such as "What can go wrong?" and "What are the consequences?"

Shah et al. (2015) proposed a method that leverages a conditional value and the perspective to manage risk. It was aimed at being used as a tool in the decision-making process for risk management. Though versatile, it is cited as limited in SoS use (Lopes et al. 2020).

Axelsson (2020) investigated the use of a unified approach based on systems thinking for analysing risks in SoS. The goal is to fill a gap in the SoS risk assessment arena, where there are arguments that risk analysis is static, whereas SoS do not come fully formed; they evolve, and risk analysis must therefore be continuous. Another argument is that risk analysis is done manually. Based on the STAMP model, Axelsson proposed a method through which risk can be accessed using system-theoretic models complemented by a dynamic approach.

Application of SoS Risk Analysis to Crisis Management

Tymstra et al. (2020) conducted semi-structured interviews with agencies involved in fire management in Canada to understand the strategies, policies, and preparedness procedures for managing wildfires. The study showed a need for a change in thinking toward a risk-based approach to crisis response. Tymstra et al. (2020) further draw attention to the use of risk management, using five phases: management, prevention, mitigation, preparedness, and response recovery.

Lunde et al. (2021) undertook a study on safety science in Norwegian avalanche rescue operations. The study set out to reassess emergency responses to these avalanche situations. The STAMP model and its techniques were used as the methodology adopted to challenge critical assumptions in the complex rescue system. The study presented a good basis for the application of the risk assessment method in a rescue operation. It relates well to our study, as avalanche rescue is a good example of SoS risk analysis. Lunde et al. (2021), on the other hand, identified a research gap regarding the attainability of normative managerial constraints in a dynamic and constantly changing rescue environment.

As can be seen from related works, a more holistic method of risk assessment at the SoS level is still required; the method should also fill a gap in assessing risk in a dynamic environment.

CASE STUDY: THE 2014 VÄSTMANLAND FOREST FIRE RESCUE OPERATION IN SWEDEN

This research was undertaken to identify characteristics of risk in a SoS and a case study was used. The scenario was a 2014 forest fire in the Swedish region of Västmanland. It was the largest wildfire in the history of the country. This meant it took a lot of effort to put out the fire, and for this reason, the event has been well investigated and documented in several public reports.

The fire started on July 31, 2014, and lasted two weeks before being officially declared suppressed. It has been estimated that the fire covered an area of 150 km^2 in three municipalities in Västmanland. One person died and another was seriously injured, while approximately 1000 people and 2000 animals were evacuated (Uhr et al., 2016; The Forest Fire Investigation, 2015). In addition to these losses, an economic loss of 1 billion Swedish crowns was estimated in connection to the forest fire and included 1.4 million cubic meters of damaged timber, 15,000 hectares of damaged forest, and over 70 buildings burned (Lidskog et al., 2019; MSB, 2015).

The fire rescue operations were initially handled by two municipalities, according to the prescribed routine. However, since it affected two neighbouring municipalities, there were coordination problems, and eventually, the national government took over operations after declaring it a national crisis. The crisis management committee was then activated.

During the fire rescue operation, the fire presented unusual characteristics, creating a big challenge for the operation. For example, the fire was able to jump obstacles such as a body of water, and its speed and direction frequently changed because of weather conditions (MSB 2015).

A large rescue operation involving firefighters from the three affected municipalities and other parts of Sweden emerged. It also involved the home guard, land and forest owners, private citizens, voluntary organizations, and help from external helicopter services from outside Sweden. All these independently managed organizations joined and collaborated as one organization in the fire rescue operation. Continuous information exchange was crucial in establishing and maintaining the collaboration.

At the start of the rescue operation, the initial setup was that the two involved municipalities were part of a cluster called the Mälardalen fire federation, which shared fire rescue experiences and coordinated the rescue operations of its members. The two municipalities were the first CS of the SoS for the fire rescue operation to respond to the rescue call on July 31.

In the initial hours of the operation, the SoS had about 30 firefighters and a civilian helicopter. The situation worsened, and as the crisis unfolded, the SoS evolved as follows:

The firefighters from the two municipalities were joined by the coast guard and home guard, who brought in water bombing techniques. A helicopter waterbombed the left flank of the fire on the evening of July 31 between 20:45 and 21:00 (MSB, 2015). Additional resources were added the next day. For example, three helicopters continued to do the water bombing on August 2. The rescue service also relied in part on volunteer local farmers, contractors, and private individuals who watered the roads, cut down forests, that fell along the roads, etc.

However, the fire continued to grow, and as it got out of control, there were also coordination issues. On the afternoon of August 3, the County Administrative Board of Västmanland began establishing a crisis organization and later took control of the operations of the municipalities. The new crisis SoS structure at the height of the

crisis comprised "several official organizations (Fire and Rescue Services from other parts of Sweden, the Armed Forces, the Police, and other governmental organizations, etc.) together with private companies and voluntary groups engaged in the response" (Uhr et al., 2015). Additionally, international help was received from Italy and France, which included four scooping planes. With these resources in place and with changes in weather for the better, the fire was eventually put under control by August 11, 2014.

METHODOLOGY

We will now describe the methodology used to analyse the Västmanland fire rescue operation from an SoS risk perspective. The section describes how data was collected and gives an overview of the procedure for analysing it.

Data Collection

The data for the case study described above was gathered by applying the data collection techniques suggested by Lethbridge et al. (2005) to the documents of the incident. The data sources included the following types of documents:

- Reports written because of government requests, such as investigation reports
- Reports written following contingency agencies' requests
- Scholarly articles that are written on the case
- Reports for fire departments from affected municipalities
- Media reports

The study found 20 documents related to the Västmanland fire as suitable, and that formed the basis for this paper. In total, the documents contained 1228 pages.

Data Analysis Procedure

The approach taken to analyse the data is the thematic coding approach (Strauss and Corbin, 1998). Each material selected for the study was read to identify sets of information indicating sources of risk. These were coded for further analysis to identify characteristics of risk in the SoS. An initial set of codes related to fire rescue was used as the starting point for coding text for themes of characteristics that form sources of risk. Additional codes identified were added during the entire coding procedure. These initial codes were used for thematic analysis.

The coding was done using NVivo software to extract identified characteristics of the data and align them to codes from all the data collected (Strauss and Corbin, 1998). The coding focused on identifying risk sources in the fire rescue operation SoS, by addressing the question and picking indicators of risk sources that emerged during operations in documents on the Västmanland fire rescue. This approach was taken because it provides flexibility in analysing the data. Additionally, the data is available so an indicative method such as this thematic coding that allows for the search for meaning in the data that is already provided is better suited.

The STAMP method was then applied based on the coded data for analysis of characteristics of sources of risk. The purpose of this was to get an understanding of how well an existing state-of-the-art method could deal with SoS-specific issues.

ANALYSIS

In this section, we provide a report on the analysis of the data for the study. The STAMP model, with STPA (System Theoretic Process Analysis) method, was used for analysis.

The initial steps followed are outlined in Figure 2, based on (Leveson and Thomas, 2018).

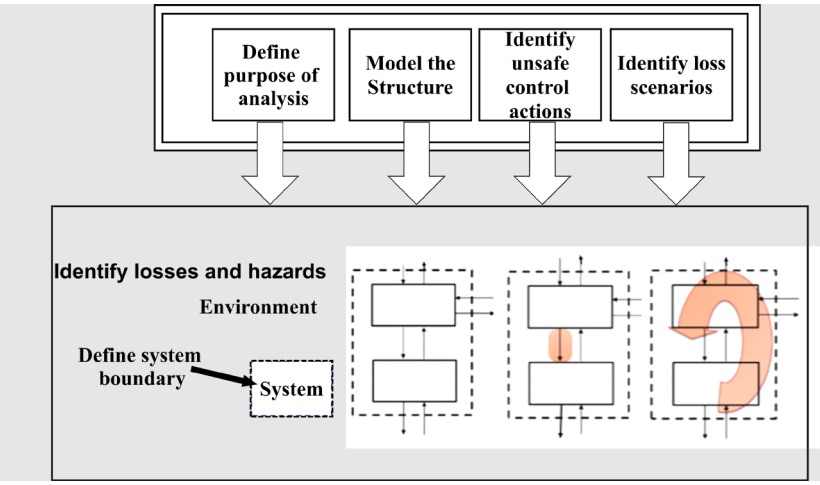

Figure 2: Overview of the risk analysis method

Define the Purpose of the Analysis

The first step defined the purpose of the analysis and consisted of the identification of the following:

1. System of interest, which is in our case the fire rescue operation SoS.
2. Losses to be prevented.
3. Hazards.
4. System constraints.

The system of interest under review embraces all systems and activities within the realm of Sweden's Västmanland fire rescue operation of 2014.

In the following subsections, we outline examples of losses, hazards, constraints, and unsafe control actions as part of the systems analysis performed through the application of the STAMP method. The examples are chosen with a focus on SoS-related characteristics.

Losses

Several authors and reports, including Lidskog (2019) and MSB (2015), outlined the following major losses (labelled L1 to L4):

> ***L1.*** *Loss of life or injury to people.* During the fire, a person died because of being caught up in flames, and one other person was seriously injured.
>
> ***L2.*** *Material losses.* Material losses included over 50 buildings and over 1.4 million cubic meters of timber.
>
> ***L3.*** *Environmental losses.* Over 14 000 hectares of forest were burnt, affecting ten registered key biotopes.
>
> ***L4.*** *Economic losses.* The total economic loss was estimated at 1 billion Swedish Crowns.

Hazards

A hazard is a system state or set of conditions that, together with a particular set of worst-case environmental conditions, can cause harm or loss (Leveson and Thomas, 2018).

Data from the documents and reports written about the case study was analysed, and the data was coded to isolate hazards in the fire rescue operation. Thus, for the fire rescue operation, conditions that could lead to any of the

Figure 3: Examples of different pieces of information indicating extracted hazards extracted from the source file (MSB,2915 Sjökvist, 2015)

Category	Hazards
Environment	On Monday, August 4, it was very hot, and the humidity was low, which meant a very high risk of rapid fire spread.
Operational	The rescue services carried out various initial efforts but were unable to surround the fire.
Organisational	It then took until Monday 4 August before the rescue managers in the affected municipalities gathered and agreed to ask the county administrative board to take over responsibility for the rescue work

losses L1 to L4 in worst-case scenarios were systematically identified. A sample of coded pieces of data from the sources extracted from NVivo is illustrated in Figure 3.

A list of hazards that can be mapped to one or more losses from L1 to L4 was produced using the STAMP guide (Leveson and Thomas, 2018, p. 19), which suggests the format:

<Hazard specification> = <System> & <Unsafe Condition> & <Link to Losses>.

Examples of hazards are listed below, with losses that could result indicated in the brackets:

H1: The forest fire operation had insufficient capability

H2: The available resources were insufficient for the forest fire operation

H3: The actors during the forest fire operation were inadequately prepared

H4: During the fire rescue operation, there were hot temperatures, low humidity, and sudden changes in wind direction.

These examples also indicate possible locations of hazards in the SoS structure, with H1 being located in the design of the SoS, H2 indicating that the SoS has too few CS of various kinds, and H3 being caused by issues within a certain CS.

The hazards identified were later refined and categorized as follows:

- *Environment hazards*. This included all hazards that relate to environmental factors that had the potential to worsen the fire crisis and therefore create risk for the fire operation. H4 was included in this category.
- *Operational hazards*. These included all hazards that emerged because of interactions in the SoS for example resources becoming insufficient as the crisis worsens giving rise to hazard H2. Another example in this category is if the capability of actors in the SoS becomes insufficient as the crisis worsens, giving rise to H1.
- *Organisational hazard*. Inadequate preparedness and unclear roles were included in this category, which created hazard H3.

System Level Constraints

Using the list of hazards created after the coding process, a list of system constraints was derived. The list follows the format outlined by the STAMP method (Leveson and Thomas, 2018, p. 20):

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

Alternatively, the structure can be:

<System-level constraint> = If <hazard> occurs, then <what needs to be done to prevent or minimize a loss> & <Link to Hazards>

Examples of system constraints labelled C1 to C3 are listed below (with hazards being addressed indicated in the brackets):

C1: The forest fire operation must have sufficient capability [H1].

C2: If a forest fire operation has insufficient resources during operation, then the insufficiency of resources must be noted, and action is taken to acquire the resources [H2].

C3: The CS must have adequate preparedness for the SoS operation [H3].

Model the Structure

Following the method being used for analysis we next model the system of interest. We first identify roles and responsibilities in the fire operation to help us identify all the controllers in the model. Their actions will give us input into the system. Included should be the feedback mechanism which will form the output. Together, these types of control actions model the information exchanges between systems and elements. Considering the resulting hierarchy of operation structure during the fire operation, we can identify the controllers from the initial organizations involved in the fire rescue operation. The initial setup of municipalities was that the involved municipalities were part of a cluster called the fire federation that shared fire rescue experiences and shared in the rescue coordination of members. Thus, the controllers were:

1. Fire federation
2. Heads of fire departments
3. Municipality heads
4. Firefighters' team leader
5. Firefighters

As can be observed from Figure 4, the SoS representing the crisis management organization during the fire operation was initially small. However, during the operation, the SoS evolved into a larger crisis. 2300 people participated in the operation, which included several agencies, police officers, soldiers, firefighters, forestry workers, volunteers, and foreign helicopter crews (Bynander, 2019). The evolved crisis organization is illustrated in Figure 5. This illustrates a common characteristic that can often be observed in SoS, namely that the structure evolves. However, control structures in STAMP are usually static, which poses a challenge when applying the method to SoS. The bigger the organization, the more sources of risk there are.

Identify Unsafe Control Actions (UCA)

After creating the system model, STAMP provides a structured method for systematically analysing the model to identify unsafe control actions. There are four reasons why a control action could be unsafe:

1. A control action required for safety is not provided or is not followed.
2. An unsafe control action is provided that leads to risk.
3. A potentially safe control action is provided too late, too early, or out of sequence.
4. A safe control action is stopped too soon or applied too long.

According to STAMP (Leveson and Thomas), unsafe actions have the following components:

<Source> <Type> <Control Action> <Context> <Link to Hazards>.

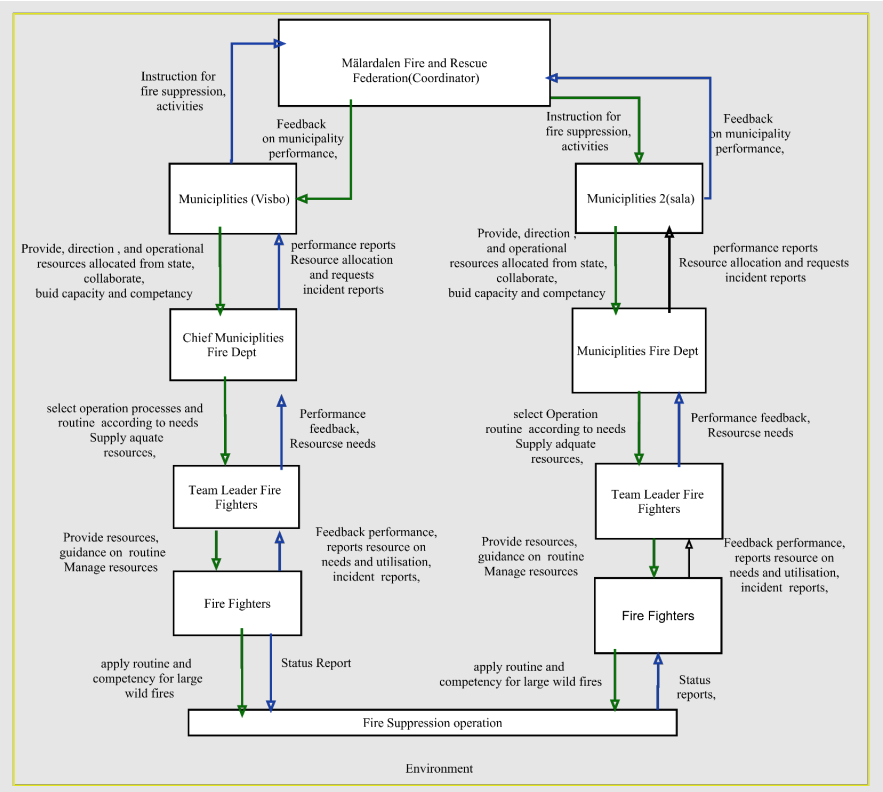

Figure 4: Activities at the start of the fire

The following are examples of UCA, with the associated hazard indicated in brackets.

UCA1: If sufficient capacity is not provided during the fire rescue operation, then the fire will not be suppressed [H1].

UCA2: If resources are not provided during fire rescue operations when available resources become inadequate, then the fire will not be suppressed Loss of life or injury to people will occur [H2].

UCA3: When actors are not prepared during a fire rescue operation, the operation will be prolonged, and death, injury, and loss of material could occur [H3].

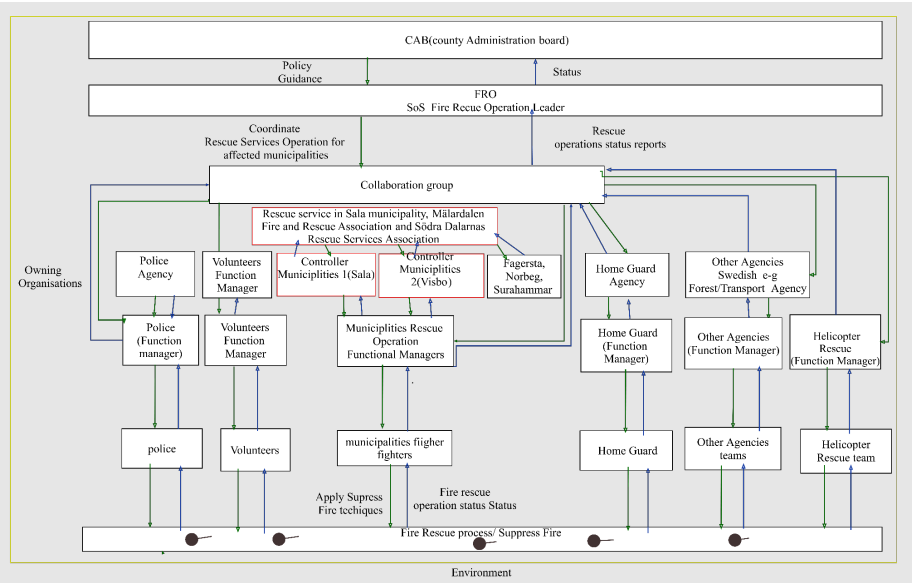

Figure 5: *Activities during the forest fire crisis. System boundary includes all organizations in this process (within yellow border). The black dots show emerging latent risk characteristics in the controlled process. The original organizations in the SoS are shown in Red.*

The above unsafe control action indicated sources of risks included characteristics such as preparedness, and insufficient capability, among others. UCA3 is of special interest since it illustrates an issue created at an earlier stage when the SoS had a different structure.

Identify Loss Scenarios

Using the unsafe action, Scenarios under which losses can occur were itemized, an example is given below:

> **Scenario for UCA1** The system (SoS) requires resources that exceed available capacity, the controller had believed that available capability was sufficient.
>
> **Scenario for UCA2**: The system (SoS) requires resources that exceed available resources.
>
> **Scenario for UCA3**: The system (SoS) requires CS to have processes, tools, techniques, resources, and tools prepared for SoS operations when they are not available.

Observations During the Application of the STAMP Method

We now discuss additional observations made as we applied the STAMP method to the CM SoS.

Commented [AJ1]: We uses both method and approach - look over all uses of STAMP and find a way to express it the same all through the article. The same for use om CM SoS instead of writing sometime the words and some time CM.

Using the method in the STAMP approach outlined in the analysis, we were able to identify the hazards in the SoS organization outlined in the literature that was a basis for the study.

However, we also noted that some elements that posed no risk at the start of the operation became risks as the organizational structure evolved. To capture the emergence of these risks, we analysed the data by slicing the timeline into frames during the operation. Each frame represents a period when the SoS structure was static, allowing for the application of the STAMP method. For example, one frame was at the start of the operation when two municipalities were involved, and another was at the time when the fire was out of control with maximum organization interaction.

The frame concept can be used to track failures across dynamic and transitory components of the system (Igarashi and Marais, 2022). It is extended from the arguments that “resident pathogens” or latent human failures generated

and preserved within a system, are embedded in the physical artifact (Reason, 1990; Love et al., 2009). Originating from one or more defective processes upstream in the system, "their interconnections can be defective and can contribute to propagating the pathogen across frames" (Igarashi and Marais 2022).

Using the frame concept, we were thus able to pick out the latent risk that became active as the SoS crisis evolved. For example, in the list below from (MSB 2015; Uhr et al, 2015), these sources of risk before SoS evolved were dormant or latent risk sources that become hazards during CS interactions in the SoS in later frames:

1. The non-updated maps available in the fire trucks at the start of the journey became hazardous when firefighters were unable to use them to locate the fire.
2. Uncalibrated instruments, that were available and in good condition, but could sometimes not be used during operations because they were not properly calibrated.
3. The low-resolution of satellite pictures could not show proper pictures of the fire sources.
4. The mobile communication devices that had battery lifetimes of 12 hours, were considered adequate when there is no crisis, and hence no spare batteries were provided. This was a source of risk because communication became difficult for rescue workers who worked in the forest when battery power ran out.

It should be noted that these risks are primarily information system related, thus stressing the importance of communication in the SoS.

DISCUSSION

The focus of this paper was to identify what characteristics of risk exist in an SoS and to evaluate the suitability of available methods by using one of them for risk analysis. The study also seeks to suggest a direction research could take for developing much-needed holistic methods for risk assessment for SoS

As discussed, earlier research indicates there is a need for a holistic approach and methods of risk assessment in risk management because current methods assess risk in individual systems of the SoS or reflect a static structure, not a changing state.

The analysis suggests that the STAMP method, when applied to an SoS exemplified by Sweden's 2014 forest fire, is effective in identifying some sources of risk in an SoS. When applied, the method's procedures were able to provide specific elements from the data that could be applied to the system of interest. These elements included identified hazards or sources of risks, system constraints, and requirements. Subsequently, control actions were also derived for the system. Thus, STAMP can identify risk in a static structure by analysing loops and feedback at a static moment in time.

However, there were also certain weaknesses, primarily related to the dynamic evolution of an SoS.

Dynamic Nature of SoS

The SoS dynamic nature in the case of forest fire was reflected in characteristics of risk during interactions and information exchanges within the system. For example, when the study analysed the data to determine hazards and when they could occur, the sufficient capability of a static system at the start of the operation was no longer sufficient during the operation of the system.

Similarly, as the crisis worsens and the SoS evolves, planned resources become insufficient, and capabilities previously deemed adequate becomes insufficient.

A significant observation is that, when the STAMP method is applied at the start of the operation, it does not capture hidden risks that emerge later. Equally, when applied at the height of the crisis, the STAMP method does not show the source of risks that may have contributed to escalating the crisis.

Thus, the analysis supports the arguments in the literature that emergent behaviour is a key factor in determining all sources of risk in SoS. This implies that the dynamic structure of an SoS comes with additional risk sources that require methods of addressing SoS in its dynamic state. We validated our finding above by using the frame concept (Igarashi and Marais, 2022) to capture the changing risk dynamics of the operation with two, time slices of operations, as illustrated in the control structures, in the analysis section. The STAMP method could then be applied to these time slices or periods of operation. This will allow to capture risks in a dynamic state, for example latent risk that become visible during this system state.

Latent Risk

Additionally, the analysis also suggested that risk can be dormant in an individual system and become a hazard in an SoS. This can be seen in themes of data that indicate delays in acting or making decisions during the fire operation. A good example of such a scenario is where initial efforts to locate the fire were delayed by over 40 minutes due to outdated maps.

Implications and Further Study

This study set out to identify risks in an SoS using one of the widely used methods for risk analysis and to evaluate, the effectiveness of the method when applied to SoS. The immediate practical application is that existing methods like STAMP can be used to derive risk characteristics with the high-level system constraints and provides a valuable direction on how risk can be handled in a SoS for existing static organisational structures. Hence, we acknowledged the existence of methods for risk assessment and through the evaluation of a popular method STAMP, we confirm that these methods are useful SoS risk analysis.

However, our results show that it does not capture all risks emerging from an SoS during its evolution. To validate this result, we employed the frame concept (Igarashi and Marais 2022) defined above, to explore the existence of such risks and isolate their source in the scenario for our study.

Our contribution to academia is to add a direction towards which research could take for designing methods that include both the static and dynamic nature of SoS to address all sources of risk.

“The world is evolving and plans need to be updated regularly and, if it is necessary, adaptations take place. Inappropriate actions cause even worse consequences for organisations”.(Khodarahmi,2009, P 225).

For practitioners, until holistic methods for risk assessment are achieved, our work has provided a guide to an interim way of dealing with risk assessment in SoS which is a combination of the STAMP and the frame notion.

Although this approach is feasible, further research is needed to refine the method. One direction is to reduce the analytical effort, by reusing parts of the analysis across frames, for those structures that did not change. For this, information system support would be useful. Another direction is to study the transition between frames, and what risks are related to that.

Our study was limited to one case study. We seek to address the research question by evaluating the method with other case studies as part of the continued research into alternative methods for SoS risk analysis. It also seeks a method that includes the dynamic nature of the SoS structure as well as latent risk.

The study, aimed at identifying characteristics of risks in the SoS, using an existing method, in this case, STAMP.

The study also aimed to evaluate an existing method on its effective use for the risk assessment of SoS.

Results support existing studies that suggest that risks in an SoS are different at any given time in that they could arise from emergent behaviour and therefore require a different approach to risk analysis. The study also contributes to the research by presenting potential directions for research on SoS methods

We recommend refining existing methods to include ways to handle characteristics of risk not well captured and addressed in current methods for SoS risk analysis, for example, latent risk. A more complete model of an event like a forest fire, with many stages of changing structure, becomes rather complex. Therefore, there is also a need for information system support in the analysis of the SoS. This is a key area for further research.

CONCLUSIONS

The paper presented an initial analysis of a crisis, in a situation that can be viewed as a system of systems.

The STAMP method was used to trace characteristics of risk during the interactions of SoS, a concept that can be extended to include the convergence of crisis management during a given crisis.

Initial results show that STAMP is useful in this process and our study was able to isolate characteristics that included inadequate preparedness, and insufficient capability, among others.

Our continued study seeks to further validate this result with another case study and provide a simulation of the process. The final product is a complete process for risk analysis for SoS.

ACKNOWLEDGMENTS

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

REFERENCES

Arnold, R. D. and J. P. Wade (2015). A Definition of Systems Thinking: A Systems Approach. Procedia Computer Science 44: 669-678.

Axelsson J (2019) A refined terminology on system-of-systems substructure and constituent system states. p.^pp. 31-36. IEEE.

Axelsson, J. and A. Kobetski (2018). Towards a risk analysis method for systems-of-systems based on systems thinking. 2018 Annual IEEE International Systems Conference (SysCon), IEEE.

Baumgart S, Fröberg J & Punnekkat S (2017) Analyzing hazards in system-of-systems: Described in a quarry site automation context. p.^pp. 1-8. IEEE.

Benali M & Ghomari AR (2016) Information and knowledge driven collaborative crisis management: A literature review. p.^pp. 1-3. IEEE.

Boardman, J. and B. Sauser (2006). System of Systems-the meaning of of. 2006 IEEE/SMC International Conference on System of Systems Engineering, IEEE.

Bynander, F. (2019). Only trees burning? The Mid-Sweden Forest Fire of 2014. In *Societal Security and Crisis Management: Governance Capacity and Legitimacy* (pp. 115–132).

Cloutier, R. and R. Griego (2008). Applying object oriented systems engineering to complex systems. 2008 2nd Annual IEEE Systems Conference, IEEE.

Dahmann J & Henshaw M (2016) Introduction to systems of systems engineering. Insight 19: 12-16.

Dahmann JS (2015) Systems of systems characterization and types. Systems of Systems Engineering for NATO Defence Applications (STO-EN-SCI-276) 1-14.

de Souza Lopes S, Vargas IG, de Oliveira AL & Braga RTV (2020) Risk management for system of systems: A systematic mapping study. p.^pp. 258-265. IEEE.

Gandhi SJ, Gorod A & Sauser B (2012) A systemic approach to managing risks of SoS. IEEE Aerospace and Electronic Systems Magazine 27: 23-27.

Gomez M, Kim Y, Matson E, Tolstykh M & Munizzi M (2015) Multi-agent system of systems to monitor wildfires. p.^pp. 262-267. IEEE.

Guide, A. (2001). The project management body of knowledge (pmbok® guide). Project Management Institute.

Igarashi T & Marais K (2022) Construction System Failures: Frame Notation of Project Pathogens and their Propagation Across Time and System Hierarchy. INCOSE International Symposium 32: 419-433.

Khodarahmi E (2009) Crisis management. Disaster Prevention and Management: An International Journal 18: 523-528.

Kinder A, Henshaw M & Siemieniuch C (2015) A model based approach to system of systems risk management. p.^pp. 122-127. IEEE.

Köhler S. 2018. Skogsbranden i Västmanland 2014. (Report No. 5143950).Länsstyrelsen Västmanland.

Lethbridge TC, Sim SE & Singer J (2005) Studying software engineers: Data collection techniques for software field studies. Empirical software engineering 10: 311-341.

Leveson N, Daouk M, Dulac N & Marais K (2003) Applying STAMP in accident analysis. p.^pp. 177-198. NASA; 1998.

Leveson N (2004) A new accident model for engineering safer systems. Safety science 42: 237-270. Leveson, Nancy G., and John P. Thomas. "STPA handbook." *Cambridge, MA, USA* (2018).

Lidskog R, Johansson J & Sjödin D (2019) Wildfires, responsibility and trust: public understanding of Sweden's largest wildfire. Scandinavian Journal of Forest Research 34: 319-328.

Love PE, Edwards DJ, Irani Z & Walker DH (2009) Project pathogens: The anatomy of omission errors in construction and resource engineering project. IEEE transactions on engineering management 56: 425-435.

Maier MW (1998) Architecting principles for systems-of-systems. Systems Engineering: The Journal of the International Council on Systems Engineering 1: 267-284.

MSB. 2015c. Observer report - Forest fire in Västmanland 2014.

Persson S & Uhnoo S (2021) Dilemmas and discretion in complex organizations: Professionals in collaboration with spontaneous volunteers during disasters. Professions and Professionalism 11.

Pinto CA, McShane MK & Bozkurt I (2012) System of systems perspective on risk: towards a unified concept. International Journal of System of Systems Engineering 3: 33-46.

Prakasha PS, Nagel B, Kilkis S, Naeem N & Ratei P (2021) System of Systems Simulation Driven Wildfire Fighting Aircraft Design. p.^pp. 2455.

Quarantelli EL (1988) Disaster crisis management: A summary of research findings. Journal of management studies 25: 373-385.

Rasmussen J (1997) Risk management in a dynamic society: a modelling problem. Safety science 27: 183-213.

Risk management Guidelines: ISO 31000:2018

Reason J (1990) The contribution of latent human failures to the breakdown of complex systems. Philosophical Transactions of the Royal Society of London B, Biological Sciences 327: 475-484.

Shah P, Davendralingam N & DeLaurentis DA (2015) A conditional value-at-risk approach to risk management in system-of-systems architectures. p.^pp. 457-462. IEEE.

Salmon PM, Cornelissen M & Trotter MJ (2012) Systems-based accident analysis methods: A comparison of Accimap, HFACS, and STAMP. Safety science 50: 1158-1170.

Sauser, Brian, John Boardman, and Alex Gorod. "System of systems management." *System of systems engineering: innovations for the 21st century* (2009): 191-217.

Siu N (1994) Risk assessment for dynamic systems: an overview. Reliability Engineering & System Safety 43: 43-73.

Sjökvist A & Strömberg I (2015) Rapport från skogsbrandsutredningen. Ministry of Justice: Stockholm, Sweden.

Strauss A & Corbin J (1998) Basics of qualitative research techniques.

Tymstra C, Stocks BJ, Cai X & Flannigan MD (2020) Wildfire management in Canada: Review, challenges and opportunities. Progress in Disaster Science 5: 100045.

Zeigler BP & Sarjoughian HS (2017) Modeling and simulation of systems of systems. Guide to modeling and simulation of systems of systems 3-11.