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Resilience in emerging complex intelligent systems: A case study of search and rescue

Youshan Yu[1] | Nicolette Lakemond[1] | Gunnar Holmberg[1,2]

[1]Department of Management and Engineering, Linköping University, Linköping, Sweden

[2]Saab AB, Linköping, Sweden

Correspondence
Youshan Yu, Department of Management and Engineering, Linköping University, Linköping, Sweden.
Email: youshan.yu@liu.se

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Abstract

As artificial intelligence (AI) is becoming part of complex systems and critical infrastructures, perspectives on resilience may need to be revisited. This paper focuses on the challenges and approaches in engineering design for achieving resilience in complex and increasingly intelligent systems (CoIS). Building on a case study of a system situated in the context of search and rescue (SAR) operations at sea as well as scenarios of SAR operations supported by AI solutions, it outlines challenges for organisational and engineering design in contexts where flexibility, adaptability, and high reliability are important. The findings point at resilience as a system property, made up of the constituent systems, their interaction and coordination in a system-of-systems framework. AI and autonomy in CoIS represent potentially a double-edged sword; while AI and autonomy contribute to system capabilities and resilience, they can also introduce limitations in terms of, for instance, confined operational envelopes. Achieving resilience in CoIS thus requires a holistic approach that considers constituent systems as well as their interplay, organisational factors, and the judicious balance of AI and human-based solutions.

KEYWORDS

artificial intelligence, complex intelligent systems, constituent systems, resilience, search and rescue, system-of-systems

1 | INTRODUCTION

Following the rise of increasingly complex systems in industry and society, such as chemical and nuclear power plants, transportation, and so forth, during the 1980s, scholars have explored major accidents like Three Mile Island and Bhopal (Perrow, 2011; Weick, 2010) to unravel the complexity of high-risk systems and arrive at advice to create more resilient systems and high-reliability operations (Cantu et al., 2020; Linnenluecke, 2017). Although different research streams have developed their specific definition, generally resilience refers to perspectives in systems and organisations to address unforeseen and unexpected events without severe consequences for their operation. Resilience has been addressed concerning engineering and the system itself as well as in organisational and management literature. In the literature on resilience engineering, the resilience of a system is defined by the ability to respond to the actual, monitor the critical, anticipate the potential, and learn from the factual (Hollnagel, 2013b). In management and organisational literature, resilience is usually related to high-reliability organisations and business continuity planning, employee strength, perseverance, and recovery when encountering adversity (Boin & McConnell, 2007; Cantu et al., 2020; Linnenluecke, 2017).

Major negative events such as 9/11, the economic crisis in 2008, and recently COVID-19, have brought back the focus on critical infrastructure's resilience on the research agenda in both the resilience engineering and management field (Boin & McConnell, 2007; Cantu et al., 2020; Ivanov, 2024; Linnenluecke, 2017). The focus of resilience research has somewhat shifted from the predominantly internal organisational response, intra-organisational reliability, and a focus on safety towards a focus on coping mechanisms and response strategies under environmental uncertainty (Linnenluecke, 2017). Yet, contributions that include multiple perspectives, including resilience of critical infrastructures as complex engineered systems are scarce (Linnenluecke, 2017). To our knowledge, resilience has not extensively been addressed in the context of the transition from primarily physical systems to digital-physical systems. This transition is marked by an increasing role of software-based functionality that is evident in both complex systems and organisations. The role of software-based functionality is two-folded; on the one hand, these systems become more complex which may affect resilience negatively while, on the other hand, it provides a possibility to design new levels of integrated functionality that contribute to resilience in complex systems (Lakemond et al., 2024). Currently, increasingly smart or intelligent solutions based on artificial intelligence are embedded into complex systems (Wang & Chung, 2022). One of the major consequences is that the system's boundaries become increasingly fluid as complementary systems are added and new organisational actors are contributing to system design and operation (Yu et al., 2024). This has been associated with challenges as it implies an increasingly generative nature of complex systems that still often fulfil safety-critical functions (Lakemond & Holmberg, 2022). Exploring resilience in this context requires an understanding that spans the fluid nature of the system's boundaries and the corresponding organisations involved. To address this, the purpose of this paper is to explore the challenges in organisational and engineering design for achieving resilient systems, especially in contexts where flexibility, adaptability, and high reliability are important. We particularly focus on the understanding of changing and fluid boundaries in emerging complex intelligent systems (CoIS). Examples can be found in traffic systems in which intelligent technologies (e.g., adaptive cruise control, automatic braking, or other driver-assist technologies) expand a system's focus from previously relatively self-contained automobiles into automobiles that interact increasingly autonomously with their environment. In this paper, CoIS are defined as systems that are high cost, engineering-intensive, emergent in character, display an inherent and recursive growth in diversity, scale and embeddedness, and put high demands on systems integration with digital, physical, and AI-based solutions making up the system (Hobday, 1998; Lakemond & Holmberg, 2022; Yu et al., 2024). CoIS are, with the inclusion of AI solutions, relying on, for instance, external data and cloud-based solutions, which reflects growth in intelligence and complex architectures that consist of several constituent systems in a system-of-systems (SoS) context (Yu et al., 2024). A SoS can be considered as a set of systems that interact to provide a unique capability that none of its constituent systems (technical, human or organisational) can accomplish on its own (ISO, 21841,841, 2019).

To study the resilience of such systems, the paper builds on a study of search and rescue (SAR) systems at sea. Such systems meet different operational needs, combine resources available, and adapt to emerging conditions in each rescue mission. Recognising that current systems achieve resilience mainly based on human coordination and integration at multiple levels, we study how future systems aim to benefit from artificial intelligence and autonomy both at constituent level and at SoS management and coordination levels and its potential influence on resilience. We study an extensive multiyear, evolving research and demonstration effort for such rescue systems that involve core actors in SAR.

The next section addresses the theoretical background of the study, including the emergence of complex intelligent systems and perspectives on resilience. Then, the research design and a detailed case description covering current and future approaches to SAR missions and increasingly fluid system boundaries are outlined. The implications for resilience are described in the analysis and discussion section. Finally, the main contributions and limitations of this paper are described in the conclusions.

2 | THEORETICAL BACKGROUND

2.1 | The emergence of CoIS

Complex products and systems (CoPS) are high-cost, engineering-intensive systems, and have several unique characteristics compared with mass-produced consumer goods. They are composed of many customized and interdependent sub-systems that may increase the system complexity and challenge the design and integration. System integrator firms are key actors in managing and engineering CoPS. Such engineering involves a variety of knowledge bases, several degrees of technological novelty, and a certain extent of both user and regulatory involvement. CoPS structures and strategies are usually organized around multi-firm projects that require interfirm coordination and collaboration (Acha et al., 2004; Davies & Hobday, 2005; Hobday, 1998; Hobday, 2005).

Driven by recent breakthroughs in artificial intelligence, AI-related solutions like machine learning and data-driven methods are increasingly being integrated, evolving CoPS into CoIS (Lakemond et al., 2024; Yu et al., 2024). Understanding the emergence of CoIS is crucial as they represent much of the critical infrastructure in society, such as energy, transportation, water, telecommunications, public order and safety and so forth.[1] Modern societies rely heavily on the effective functioning of these infrastructures (Boin & McConnell, 2007) which makes resilience of utmost importance. Potential disruptions may not only lead to financial losses, but also to, for example, delayed emergency responses or significant environmental harm (Bergström et al., 2015; Knight, 2002). This leads us to revisit resilience in the age of AI (Perez-Cerrolaza et al., 2023; Wang & Chung, 2022; Woods, 2019) or, more specifically, resilience in emerging CoIS.

With the evolvement of CoPS into CoIS, new conditions are emerging, not the least related to co-existing demands on safety-criticality, indicating a need for control in development and operation, and generativity as an inherent characteristic of intelligent systems associated with the evolvement and emergence of systems (Lakemond & Holmberg, 2022; Yu et al., 2024). The nature of CoIS, characterized by fluid organisational and system boundaries in a SoS context, necessitates a consideration of the bounds of generativity in system design and operation (Yu et al., 2024). Consequently, addressing resilience in CoIS requires analysis beyond the specific AI solution itself and needs to include a focus on the characteristics of CoIS, and an understanding of how complex situations with a multitude of actors and interconnected constituent systems can be navigated (Busby & Iszatt-White, 2014).

Such navigation entails engineering aspects as well as organisational aspects, including, for instance, resilience performance, technical solution design for operational resilience requirements, risk-based design processes, techniques to mitigate damage after an incident, and organisational change management enabling resilient systems (Bourrier, 2011; Fraccascia et al., 2018; Weick & Quinn, 1990; Weick & Sutcliffe, 2001; Weick, 1987). The focus on resilience has emerged in distinct research streams, each with its definitions and recommendations (Firesmith, 2019; Fraccascia et al., 2018; Hillmann & Guenther, 2021; Ivanov, 2024; Linnenluecke, 2017; Teo et al., 2017). In the next sections, first, a short background on system resilience, and then, on organisational resilience is covered.

2.2 | System resilience

Research focusing on resilience has its roots in studies of high-risk technologies and the safety of complex systems (Bergström et al., 2015; Perrow, 2011; Wildavsky, 1988). In recent times, it has been noted that complex systems operate in collaboration, interaction, and reliance on other complex systems. This has given rise to the SoS concept, which has become a crucial area of study in both engineering management and crisis/disaster management. (Fan & Mostafavi, 2019; Gorod et al., 2008; Jamshidi, 2017; Yu et al., 2024). SoS, involving a set of constituent systems, exhibit complexities on the constituent as well as the overall system level. The interoperability of SoS is designed to accommodate a wide range of possibilities and unpredictable operating environments, providing a unique capability beyond the constituent systems (Bondar et al., 2017; Ge et al., 2013). SoS are characterized by operational and managerial independence of the constituent systems, evolutionary development as well as emergent behaviour (Jamshidi, 2017; Maier, 1998). Examples can be found in the transportation, aerospace, service, energy sectors and not the least in crisis and disaster management where the constituent systems share a common goal (Jamshidi, 2017). In comparison to a system, a SoS can be considered as, with the same scope, allowing for an open architecture to incorporate desired capabilities and rapid responses to new needs in a dynamic context while making effective use of available resources.

System resilience is a critical quality, characterized by the capacity to adapt to changing situations, disturbances, or fluctuations while maintaining its functionality, safety, and reliability, it is contrasted with brittleness, which refers to a sudden collapse or failure when systems are pushed beyond their boundaries, so the systems need to have "graceful extensibility" to extend their capacity defined by their boundaries to adapt (Bergström et al., 2015; Woods, 2018, 2019). Firesmith (2019) defines resilience as "*A system is resilient to the degree to which it rapidly and effectively protects its critical capabilities from disruption caused by adverse events and conditions*".[2] System resilience involves flexibility, adaptability, and learning from past experiences to better handle future challenges. In a SoS context, system resilience expands to include quick recovery after any constituent system faults (Hosseini et al., 2016; Uday & Marais, 2015), as well as additional connection configurations between the constituents to deliberately increase SoS resilience (Watson et al., 2023). SoS resilience requires a perspective on the SoS as a whole and considering information and input from a wide range of sources, including automated responses and human input and judgement (Uday & Marais, 2015). Hence, it is worth underlining a SoS approach potentially offers increased resilience but is also at risk of creating dependencies that hamper resilience efforts (Lakemond & Holmberg, 2022).

When AI solutions are becoming integrated into safety-critical CoPS, new challenges are raised in relation to reliability, the "black-box" problem, and the need for robust verification and validation methods (Falco et al., 2021; Fjelland, 2020; Perez-Cerrolaza et al., 2023; Wang & Chung, 2022; Xu & Saleh, 2021). Currently, the emergence of CoPS into CoIS appears to become a reality in aviation, healthcare, oil and gas industry, and so forth. when AI and autonomous systems (AS) are integrated into design, operation, and management of these systems (Cai et al., 2012; Lakemond et al., 2024; Mehta & Devarakonda, 2018). Such CoIS are increasingly operating in a SoS context where system boundaries tend to be more fluid, and expanding (Yu et al., 2024). With a variety of stakeholders involved in the design, operation, and management of CoIS made up of SoS, and with an increasingly generative nature (Yu et al., 2024), new conditions for system resilience emerge, which, until now are not well understood (Uday & Marais, 2015).

2.3 | Organisation resilience

While it has been noted that SoS involve human aspects as well (ISO, 21841,841, 2019) and system resilience involves "humans-in-the-loop" (Uday & Marais, 2015), the literature on systems resilience does not tend to take an explicit organisational perspective on resilience. Especially when SoS resilience involves additional configurations to connect the constituents (Watson et al., 2023), including organisational routines and responses, organisational resilience represents part of the understanding of CoIS resilience. In the organisational domain, several central contributions have been made to organisational resilience, stressing the adaptive nature of organisations to respond to unforeseen events (Coutu, 2002; Linnenluecke, 2017; Weick & Roberts, 1993) and thereby maintain functions by mobilising and accessing the resources needed (Hillmann & Guenther, 2021). Many of the insights have their origins in disasters and accidents in potentially hazardous complex contexts, for instance through the studies in the field of High Reliability Organisations (HROs) (Cantu et al., 2020; Rochlin, 1989; Weick & Roberts, 1993; Weick & Sutcliffe, 2015). In this context, it was particularly studied how organisations responsible for, for example, nuclear power plants, air traffic control systems, and transportation systems, could actually achieve a relatively low rate of error or accidents for a long period of time (Roberts & Bea, 2001; Roberts, 1990; Rochlin, 1996). Studies have brought forward that mindfulness, in terms of an emphasis on the context and a detail that allows for a multifaceted understanding of a situation is an important aspect of resilience (Weick & Sutcliffe, 2001, 2015). It is important in achieving organisational resilience as it can support the process of sense-making of unexpected events (Weick & Roberts, 1993; Weick & Sutcliffe, 2015). Five management principles have been found to be at the centre of organisational resilience; (1) preoccupation with failure, (2) reluctance to simplify, (3) sensitivity to operations, (4) commitment to resilience, and (5) deference to expertize. As a carrier of resilience, an organisational culture that allows for flexibility and improvisation contributes additionally to organisational resilience (Cantu et al., 2020; Weick, 1987), all emphasising the importance of human engagement in resilience.

A review of influential publications on resilience in business and organisations identified five major research streams, including organisational responses to external threats, organisational reliability, employee strengths, the adaptability of business models and design principles that reduce supply chain vulnerabilities and disruptions (Hillmann & Guenther, 2021; Linnenluecke, 2017). Still, several issues remain unresolved. For instance, it has been argued that future work is necessary to better understand tensions between the importance of organisational stability and organisational change, as well as organisational reliability and organisational adaptability (Linnenluecke, 2017) which may include seemingly contradictory solutions and design choices.

Interestingly, in the domain of organisational design and management, the focus on SoS and network of networks and its consequences is not explicitly prevalent, although many contributions on, for instance, organisational ecosystems may reflect these new and interrelated ways of organising (Cobben et al., 2022; Fan & Mostafavi, 2019; Ritala & Almpanopoulou, 2017). Given the current emergence of CoIS, there is an urgent need to integrate insights from engineering as well as management and organisational disciplines to understand resilience of critical infrastructures and SoS related to them (Bourrier, 2011; Cantu et al., 2020; Firesmith, 2019; Hillmann & Guenther, 2021; Linnenluecke, 2017).

2.4 | Theoretical framework

Based on the theoretical background outlining that CoPS are evolving into CoIS, many of which are critical infrastructures in our society, it is imperative to study resilience that can be explored from both engineering/system and management/organisational perspectives. Also, the nature of CoIS as SoS, comprising various constituent systems, and situated in their often-unpredictable operating environments, resilience is considered at both the constituent system level and the SoS level. While resilience is addressed on both levels, resilience measures in constituent systems and on the SoS level may also have enabling or constraining effects on each other. Together though, they determine the overall resilience of CoIS. Following this, we formulate a theoretical framework guiding the analysis of our study (see Figure 1).

3 | RESEARCH DESIGN

This paper adopts Yin's (2017) case study method to examine the evolution of SAR operations, contrasting current practices with future scenarios involving autonomous and intelligent systems demonstrated by WARA-PS (one of the Research Arenas of a large Swedish research programme WASP that focuses on Public Safety). The case study approach was selected as it enabled us to study the relatively unique case of WARA-PS as a representation of future phenomena related to resilience in future systems aiming to benefit from artificial intelligence and autonomy and its potential influence on resilience. SAR operations, by nature, require high adaptability, flexibility, and reliability which are the key aspects of resilience. SAR is undergoing significant changes with the integration of AI solutions (Ai et al., 2019; Lomonaco et al., 2018; Queralta et al., 2020). WARA-PS is dedicated to demonstrating this, making it a suitable case of how resilience is affected by the integration of AI. By studying the activities in

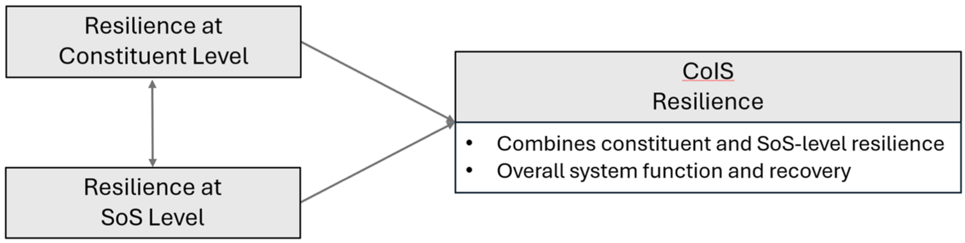

FIGURE 1 A theoretical framework.

WARA-PS that focus on SAR operations, and involve central actors in SAR, we can specifically observe how resilience is challenged, maintained, and progressing in the face of AI integration in complex and dynamic environments. This also provides insights into the broader implications of resilience in the future CoIS.

We analyze our case through a lens of the theoretical framework of resilience presented in the previous section, by looking it at both the constituent and SoS levels. First, as a benchmark, we analyze current SAR operations to understand their organisation, decision-making and technology use. Second, we focus on potential future operations with the integration of autonomous and intelligent systems. WARA-PS focuses on the development and demonstration of future technological capabilities and consists of a SoS reflecting a future coordinated variety of autonomous and intelligent systems with extensive machine learning algorithms to contribute to SAR. It uses realistic SAR scenarios that are suitable for studying engineering and organisational aspects of integrating AI solutions into the design of the system at both a system and constituent system level as well as the achievement of resilience. Our research is in line with recent research about how and what AI technologies are used in SAR operations (Nasar et al., 2023) that often involves a SoS context with constituent systems, and interactions among stakeholders, operations, resources, information and infrastructure (Fan & Mostafavi, 2019).

The case of WARA-PS can be considered as a representation of future CoIS with autonomous agents and humans coordinating aimed at accomplishing a safety-critical task. SAR operation is part of making society safe, but the operation of the system must also be safe for its operators and third parties. This study concentrates on the variety of needs that originate from an infinite range of possible SAR missions that the system may face, and the resilient response needed by a SAR system. While it is impossible for WARA-PS to anticipate all potential SAR scenarios due to the unpredictable nature of crises where new scenarios may emerge, it does incorporate several scenarios based on real-world SAR operations. The scenarios in WARA-PS include detailed activities that reflect actual SAR situations, designed to simulate crises with highly unusual and unpredictable events. By exploring SAR demonstration activities within WARA-PS, and how the scenarios for demonstration are designed and implemented, this study provides insights into the implications for resilience when generativity and criticality are combined in future CoIS.

To perform the study, extensive data were gathered throughout several years of study and through detailed observations at WARA-PS's yearly demonstrations workshops and interviews with the key informants (e.g., those involved in the core team) that have been working with WARA-PS continuously between the workshops from the years 2019 to 2023. In addition, extensive secondary information from online resources regarding SAR organisational activities was gathered and used (see Table 1 below for the main data sources of this study). To ensure an empirically robust description of the case study and a thorough understanding of the findings, each author cross-checked the emerging insights against various pieces of evidence. Any divergent interpretations were reconciled by comparing them with the data and through extensive discussions among the researchers as well as representatives of WARA-PS to achieve consistency and accuracy in the analysis.

The annual demonstration workshop of WARA-PS holds SAR demonstrations, discussions, and presentations about unmanned vehicles, autonomous agents, and the cooperation of autonomous agents and humans. Since 2019, the demonstration workshop has been held on-site with actors and visitors in Västervik, a coastal city in Sweden where actors can easily access land and water. In 2020 and 2021, the demonstration workshops were held on-site with major actors and fewer visitors due to the pandemic situation. Visitors could also join the demonstration remotely online by watching live streams about ongoing activities in 2021, the activities were recorded by film recordings and other documentation for further research. The yearly demonstration workshops from 2019 to 2023 highlight the ongoing development of research, the evolvement of SAR operations, as well as the potential contributions of digitalisation and artificial intelligence to public safety.

TABLE 1 Qualitative data sources.

Observations	Annual demonstrations' workshops that gather researchers, engineers, and visitors to show a variety of SAR scenarios using autonomous agents from the air, on the surface, and underwater. The observations were carried out in 2019 for one day, in 2020 for three and a half days, in 2021 for two days, in 2022 for two days and 2023 for one day. Data are captured by taking notes, photos, informal conversations, and recordings on site.
Interviews	Eleven unstructured interviews are conducted during the annual demonstrations' workshops. The questions are mainly related to the roles and functions of each team and its autonomous agents, what the SAR scenarios are, and how the operations are carried out collaboratively.
Online resources	Besides interviews within WARA-PS, extensive secondary data about the Swedish SAR organisations and activities are gathered through entities' websites and documents, such as the **S**wedish **S**ea **R**escue **S**ociety (SSRS) (https://www.sjoraddning.se), The Coast Guard (https://www.kustbevakningen.se), The **S**wedish **M**aritime **A**dministration (SMA) (https://www.sjofartsverket.se), The Swedish Civil Contingencies Agency (https://www.msb.se) The Swedish Accident Investigation Authority (In Swedish: Statens haverikommission) (https://www.havkom.se/)

4 | FINDINGS

4.1 | SAR at sea in Sweden

Current SAR at sea in Sweden is organized as a system that can respond efficiently during very different conditions utilising a wide range of resources, whereof just a subset is dedicated to the task. Hence, current SAR systems exhibit an ability to act as a loosely integrated system of systems with fluid boundaries where resilience mainly relies on the organisational ability to adapt to unforeseen situations and on the use of nondedicated resources. This is made evident in the following description of the organisation of SAR at sea.

The **S**wedish **M**aritime **A**dministration (SMA) is a governmental authority that is responsible for the Swedish national maritime SAR in the Swedish territorial waters of Vänern, Vättern, and Mälaren or within Sweden's economic zone when a vessel is in distress, as well as for facilitating the emergency transport of patients from seafaring vessels. The maritime SAR operation, including medical evacuations from ships, operates on a 24-h basis and is governed by the Civil Protection Act, focusing on designated areas.[3] Local municipal rescue services take care of the emergency operations on local waterways, canals, rivers, harbours, and other local lakes (**S**wedish **R**escue **S**ervices **A**gency, **S**tatens räddnings**v**erk). The Swedish Coast Guard is another civilian government agency under the authority of the Ministry of Justice that provides environmental rescue services at sea or assists other authorities in sea rescue services. Besides the governmental authority, the **S**wedish **S**ea **R**escue **S**ociety (SSRS), which receives no government financing, is involved in nearly 90% of all sea rescues in Sweden.[4] The Swedish Maritime Administration can use resources from other agencies and voluntary organisations, such as the SSRS. SSRS has been supported by membership, donations, and volunteering efforts. Its resources, such as sea rescue stations, rescue volunteers, and rescue vessels that support SSRS have been increasing. Thanks to the rapid and flexible allocation of resources, intensive periodical crew training, and close physical location of the crew, the SSRS can accomplish its aim of departing in 15 min or less from the time an alarm is received. The SSRS has close collaboration with WARA-PS with the vision of implementing SAR missions using autonomous and intelligent systems in the future. Figure 2 provides an overview of the actors in the Swedish SAR at sea.

According to the Swedish Rescue Services Agency, it is necessary to have an incident commander with the necessary qualifications that oversees all the emergency operations. Such a commander can request resources like personnel, material, or property from national or municipal authorities without seriously interrupting the providers' normal working conditions. Furthermore, the incident commander has the authority to demand private property and command or assign all individuals between the ages of 18 and 65 to assist in the emergency work to the extent that their capabilities, health, and physical conditions allow. The incident commander is thus basically forming the dynamically adapting SoS during emergency operations.

The SMA identifies three functions in SAR operations: SAR Management, Mission Coordination, and Mobile Facilities[5] (see also Figure 3).

SAR-Management oversees the overall management of the Swedish SAR organisations. This involves handling policy matters, fostering cooperation with other national rescue organisations, engaging in international collaborations and exercises, and formulating both national and international SAR agreements. SAR Management also oversees the **J**oint **R**escue **C**oordination Centre (JRCC) and assesses SAR missions for quality assurance under the SMA's guidelines.

Mission Co-Ordination has been performed by a JRCC, known as Sweden Rescue, which is situated in Gothenburg alongside the

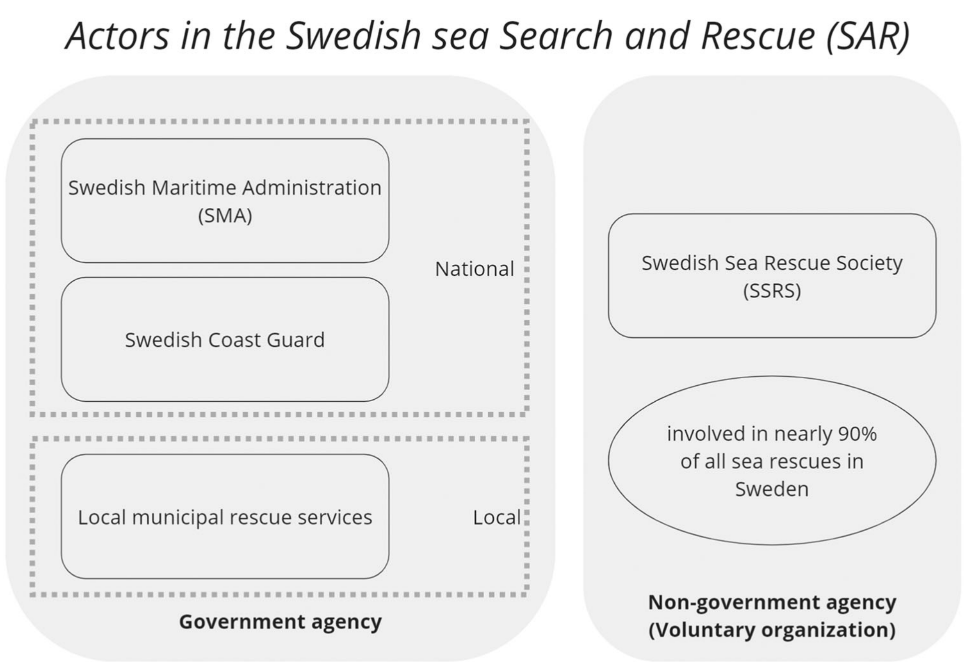

FIGURE 2 An overview of the actors in the Swedish SAR at sea.

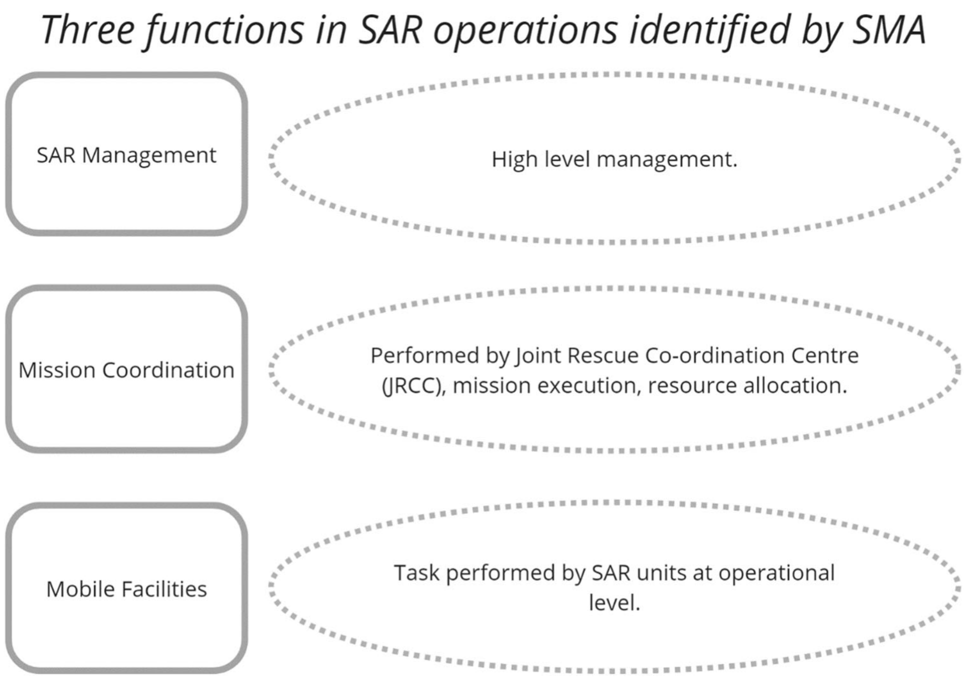

FIGURE 3 Functions in SAR operations.

Swedish Coastguard and the Defence Forces Navy Control. The JRCC is responsible for coordinating SAR missions and allocating resources such as using a helicopter to evacuate the most vulnerable passengers, for instance, during the incident at the passenger ship STENA SCANDICA on the 29th of August 2022.[6]

Mobile Facilities include the operational tasks performed by the units within the SAR mission. Sweden's coastline is divided into fifteen SAR areas. Each Traffic Area Director is responsible for ensuring the presence of sufficient Search and Rescue Units (SRUs), which can be considered as constituent systems, in their region to meet the SAR objectives. These SRUs are required to be staffed by adequately trained and competent crews. To achieve these objectives, a high level of collaboration is necessary among various organisations involved in rescue services. This ensures optimal utilisation of all available rescue units, including those primarily designated for other purposes. The Swedish Civil Protection Act plays a crucial role in facilitating and securing this interorganizational cooperation.[7]

For joint rescue services like air-sea SAR, specially trained persons are required for On-Scene Coordination, for instance, pilots with an adequate level of competence from the SMA appointed for SAR operations. The overall onsite situation, including weather conditions, ocean current, visibility, sea state, water temperature, and other relevant information shall be reported to the JRCC by the SAR units in the search planning. The duty boats/vessels with the crew have 15 min of readiness. Early information is the key to either a successful operation or a prompt SAR suspension/termination in case of uncertain risks (e.g., bad weather).[8] SAR activities and procedures are sometimes updated after an accident happened, for instance, the Swedish Accident Investigation Authority (In Swedish: **S**tatens **h**averi**k**ommission), a governmental authority, is dedicated to conducting thorough investigations of accidents and incidents. Its primary goal is to enhance safety by meticulously examining the chain of events, causes, damages, and other consequences of such occurrences. The findings from these investigations are important in informing decisions designed to prevent the recurrence of similar incidents or to mitigate their impact in the future. These investigations serve as a foundation for evaluating the effectiveness of SAR services and for improvements to the SAR services.[9]

4.2 | Increasingly intelligent SoS in SAR context

WARA-PS, or the **WA**SP **R**esearch **A**rena in **P**ublic **S**afety, is a part of the **W**allenberg AI, **A**utonomous Systems and **S**oftware Programme (WASP). As Sweden's largest research programme and a major national initiative on artificial intelligence (AI) and autonomous systems (AS), WASP gathers actors from both industry and academia to research unmanned vehicles or AS that adapt to their environments utilizing sensors, data, and knowledge. The actors in the arena include universities, industries, research institutes, and government agencies with an interest in SAR.[10]

WARA-PS experiments with building intelligent SoS including humans as well as autonomous agents (constituent systems) for public safety. It is a research arena that focuses on scenarios aimed at keeping society safe when encountering extreme situations. The arena creates an environment of real-life circumstances, by integrating the AS (drones, autonomous boats, and underwater robots) to execute SAR missions with other nonautonomous systems as well as human actors. The management of the complexity of this SoS including the interaction of humans and constituent systems involves motion planning, situation awareness, control theory, cloud computing, positioning and navigation, image processing, and resource management (Andersson et al., 2021; Domova et al., 2020).

WARA-PS serves as a research platform to explore the embeddedness of AI and AS in CoIS with a specific application focus on SAR at sea. For example, a drone-based system is made available to be able to create awareness of the situation, assess risks, and minimize response time in an early phase of SAR, an instance of such a constituent system (UAV) is demonstrated by Andersson et al. (2020) to make SAR operations faster and smarter. In comparison to the traditional SAR operations that often go over areas exhaustively without considering where victims are more likely to be influenced by terrain, population density, and disaster type. Andersson et al. (2020) propose a probabilistic model to incorporate prior information (such as maps, data about buildings, and phone traffic data), real-time updates (as UAV searches the model updates in real-time), and smart planning (plan the best search routes for the UAV to find victims as quickly as possible). By using this model, UAVs can focus on areas where victims are more likely to be found rather than searching randomly, and quickly incorporate new information and choose the most promising areas to search for next. Their results showed that SAR efforts can be enhanced, and outperform traditional strategies in various simulated disaster scenarios, especially effective in scenarios with limited or incomplete prior information, showing the constituent system's ability to adapt and learn quickly, and in the meantime to maintain safety as “instead of a separate task objective with constraints on safety, safety is the objective of this task” (Andersson, 2020, p.45).

The constituent system can operate in various modes: it can automatically adjust the position of drones based on updated information, and also supports a mixed mode. In the mixed mode, the system processes updated information in conjunction with human experience and knowledge, particularly for the management of critical and limited resources. Drones can also patrol areas to detect anomalies, triggering automatic tasks or manual interventions by humans who can notice anomalies in video feeds. The system's search function enables drones to find specific objects, categorising them as points of interest for future inspection, with the process being divided between drones based on terrain types. During rescue operations, the drone system can contribute by delivering appropriate aid to identified victims, with the system prioritising victims and selecting aid efficiently. The SoS approach highlights the adaptability, learning and resource utilization in dynamic and uncertain environments.

The vision of WARA-PS is to integrate connected autonomous vehicles and other technical solutions, together with current existing human expertize to search and rescue persons in distress. Autonomous vehicles can range from drones, autonomous boats, and land vehicles to underwater robots suggesting a wide range of operational capabilities subject to the actual situation in need. AS (or “unmanned vehicles”) can be crucial for accessing dangerous or inaccessible areas. The unmanned vehicles are equipped with sensors and positioning systems, which are essential for data collection and precision operation. Sensors can include cameras, thermal imaging, sonar, radar, lidar, and so forth, allowing for diverse data collection in various environments. AI solutions have been integrated into location positioning, situation awareness, autonomy, vehicle calibration, and so forth. in the rescue system. Based on several demonstration scenarios on how SAR has been carried out with the collaborative AS in real-life settings, it has been shown that the AS can be integrated into a Core System, even though each constituent is managed by different organisations. The Core System acts as an infrastructure integrating agents, services, and systems to facilitate coordinated operations. Central to the core system are its command-and-control functions executing decision loops, where humans and systems work together to shape, execute and follow up SAR missions, and perform a breakdown of the mission into tasks that can be handled more independently.

In the case of WARA-PS, missions are executed through the allocation of an evolving set of tasks that together address the mission. Each of the tasks can be allocated to a human team, or to an AS, or some types of combination. In a sense this system mimics the command-and-control functionality of current rescue systems utilizing a wide range of actors.

The collaborative rescue system is flexible to integrate other AS like the autonomous water jet into the command-and-control platform to expand the rescue capability. AS are capable of collaborating in different areas, they can work alongside the human rescuers during the rescue operation. The flexible and adaptive features of AS make them suitable to be used for SAR and showcase how different systems can interact and function together in complex environments.

Over 5 years of demonstrations within WARA-PS, the focus has evolved from early demonstrations just focusing on the ability to perform collaborative missions with heterogenous systems, via a focus on unknown, less predictable scenarios, to more lately focus on resilience aspects such as the ability to replan when a plan or a technical system fails, or to replace a technical systems task execution with a human effort.

5 | ANALYSIS AND DISCUSSION

WARA-PS has been envisioning and exploring future SAR at sea with intelligent systems. Through its demonstrations, it has illustrated how a heterogeneous multi-stakeholder group of actors, AS and other resources temporarily can be brought together to carry out a specific task in an intelligent way. Each part of the system has its specific focus, but the overall system has a common goal that gives meaning to the SAR collaboration.

SAR operations for people in the water are essential for ensuring maritime safety, as they involve high levels of unknowns. Therefore, these operations require a resilient system that can cope with unforeseen and complex situations where the mission is often incompletely defined and evolves over time. Based on the study of WARA-PS, it appears that autonomous constituent systems can be allocated on task level. Resilience on a task level is connected to the ability to execute a task and is thus relatively limited. Expanding this, resilience on an overall SoS mission level depends on each constituent system's resilience.

Still, the implementation of AI and AS as part of the resources among the constituent systems can enhance resilience when tasks can be executed in a new or safer way or when new tasks can be defined. For instance, an autonomous agent can contribute with a new degree of situation awareness as well as is able to enter dangerous situations without risking the loss of additional human lives. On a task level, AI and AS can also constrain resilience as their use may be more confined in their operation envelope and less flexible as fully human-operated systems.

While resilience in CoIS can be viewed from a constituent system level, resilience on a SoS level appears as more than the sum of the resilience of its constituent systems. In the studied case there is a relatively direct mirroring between constituent systems performing tasks, and a SoS performing missions, while this could be expected to include more complex relations when expanding opportunities for recombination. Additional approaches on the SoS level can contribute to the overall SoS level resilience. For instance, a task breakdown approach allocates the resources and the role of the constituent systems in the overall mission. Such a task breakdown approach and allocation of resources can contribute to resilience in a positive way. Also here, the use of additional AI and autonomous solutions on the SoS level, for instance in assisting task breakdown and resource allocation quickly and continuously, can contribute to mission-level resilience. At the same time, this could also imply new types of risk connected to, for example, difficulties in sharing information and planning of different task execution strategies with humans and AS involved.

Hence, on the one hand, it appears that AI and autonomy have the potential to contribute to better situation awareness in complex scenarios as well as may lead to a better understanding of alternative action strategies enabling a more resilient approach to a mission. On the other hand, it appears that resilience might be hampered by approaches that involve AI and autonomy that do not allow for the same level of combination and recombination possibilities for tasks as current SAR systems do. This reflects the role of intelligent solutions in CoIS as a double-edged sword (Lakemond & Holmberg, 2022) and is reflected in Figure 4.

In addition, when SAR is facing atypical, high-impact scenarios that may not be covered well by existing protocols or knowledge, and missions can change as new information becomes available, circumstances evolve or conflicting goals emerge, a dynamic response system is necessary. This may include adapting to new objectives or resource constraints as they arise and require balance between safety which may require some degree of predictability or judgement and flexibility to adapt to emerging situations. This requires an evolved perspective on resilience (Boin & McConnell, 2007), beyond retrospective responses, and involves AI solutions, and autonomous constituent systems collaborating with human actors.

In WARA-PS, the core system is a salient characteristic of the collaborative autonomous rescue system. It is a platform

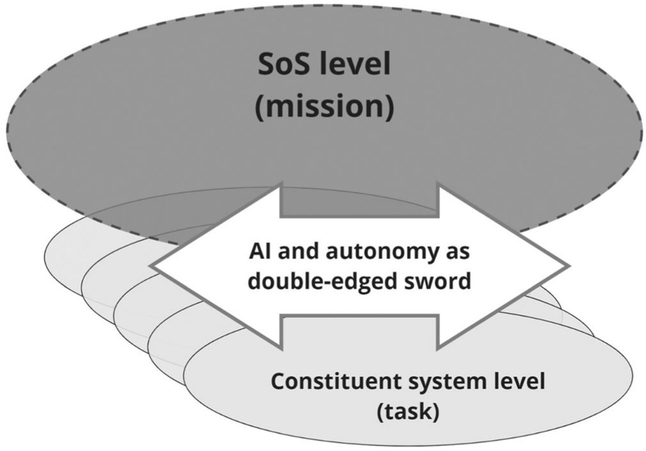

FIGURE 4 AI and autonomy as a double-edged sword for resilience on SoS and constituent level.

infrastructure that supports SAR activities, including data collection and handling, modelling, and monitoring, task planning, autonomous agents' integration, and so forth. Previous research has shown that data analytics and artificial intelligence supplemented by real-time monitoring systems support the detection of short-term deviations and the planning of a recovery strategy both organisationally and technically (Ivanov, 2024). It has been noted that a change in organisational strategies in the future intelligent rescue systems is taking place, by expanding the platform and integrating new functionality to enhance resilience and in the meantime maintain critical control (cf. Lakemond et al., 2024). Organizers and designers of collaborative intelligent SAR systems face delicate challenges in combining integration and fluidity for efficient and resilient emergency responses. These insights expand existing insights on resilience.

SAR systems cannot anticipate or prepare for every possible scenario, but they need to be able to adapt and respond to the unexpected. The resilient challenges with the SAR system lie in managing different aspects of the mission's goals. Linnenluecke (2017) and Hillmann and Guenther (2021) have suggested resources, capabilities, behaviours, and organisational structures that can promote resilience in a range of contexts. In the current SAR operation such as the SSRS does, resilience is achieved through extensive training for a wide range of missions, and training on combining and recombining resources depending on specific situation characteristics. Further, as discussed above, an ability to efficiently allocate and utilize external resources in more or less integrated manners plays an important role in resilience and the ability to respond to the unexpected and maintain the function (Hillmann & Guenther, 2021). Resilience can be further expanded by resource expansion (building more sea rescue stations and units across Sweden, recruiting more volunteers), increasingly frequent crew training (several times in 1 month), and closer collaboration with other organisations (government authorities, WARA-PS, etc.), so that the organisation grows through learning and adaptation (Hillmann & Guenther, 2021).

In future CoIS, it seems that Weick's (2010) roles of cognition, action, and sensemaking in crisis management will partially be performed by autonomous agents instead of human beings, and partially by the joint human-AS collaboration. It can thus be inferred that resilience related to CoIS alters perspectives on HROs with its focus on mindful organising as a safety culture (Cantu et al., 2020; Roberts & Bea, 2001; Sutcliffe, 2011; Weick & Sutcliffe, 2015). Rather, it seems to become necessary to consider the known/unknown data completeness, or rather an incompleteness, when designing and building resilience in collaborative autonomous systems. To effectively implement built-in flexibility in a SoS level, particularly in the context of CoIS, it is necessary to account for the human factors (Hollnagel, 2013a; Lundberg & Johansson, 2021; Rankin et al., 2014). The diverse range of human behaviours can be a valuable asset in situations unanticipated during the system's design or when events exceed the usual or intended operational boundaries. This necessitates a system's capability to extend beyond its standard scope, adapting and responding effectively to such challenges. Continuous interaction and coordination between humans and intelligent systems should be taken into consideration, so the systems are not just independently capable but also able to work effectively in collaboration with humans to support joint activities (cf. Bradshaw et al., 2013). When autonomy in systems increases, it changes the nature of tasks and work, which necessitates a reconfiguration of human roles, skills, and responsibilities, the control processes may shift between humans and AS, or there is perhaps a need to have a joint control system, to handle different levels of autonomy interacting in dynamic situations (Cimolino & Graham, 2022; Lundberg & Johansson, 2021; Simon, 1987).

An important implication from this study is that resilience in CoIS appears not to be solved in a simple way but involves resilience to be transformed into other forms of issues that need to be managed through further effort by a variety of organisations. Thus, in CoIS, resilience is rather a broader quality and may include the relationship between those who rely and those who are relied upon (Busby & Iszatt-White, 2014; Rochlin, 2011). Based on our case study, this can be summarized in a model (see Figure 5) that incorporates the multiple analytical facets of resilience in complex systems based on our theoretical framework.

6 | CONCLUSION AND CONTRIBUTION

This paper sets out to understand resilience in the context of emerging CoIS when AI and AS become an integrated part. With a specific purpose of exploring the challenges in organisational and

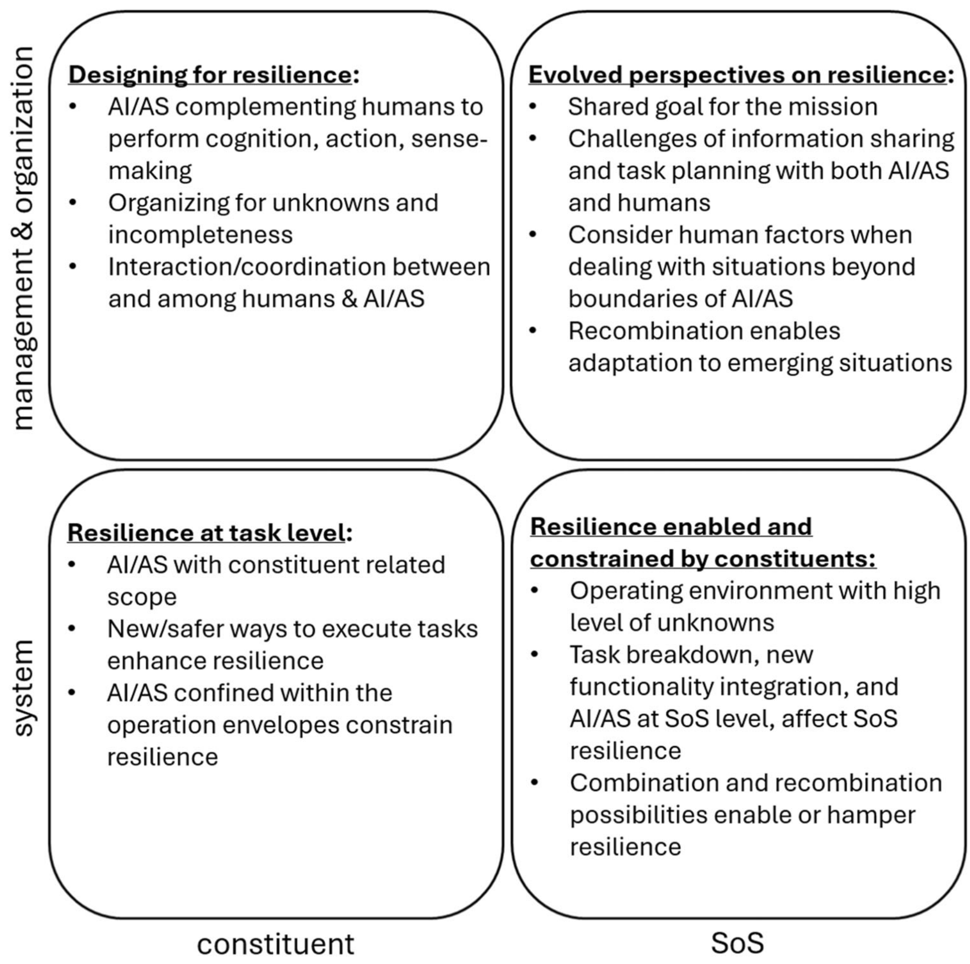

FIGURE 5 Aspects of organisational and system resilience with AI/AS.

engineering design for achieving resilient systems, especially in contexts where flexibility, adaptability, and high reliability are important, the findings point to several important contributions.

First, resilience in the context of CoIS increasingly implies a SoS context, involving several constituent systems that may be dominated by hardware, software, human beings, as well as increasingly autonomous and intelligent features through the integration of artificial intelligence. Understanding resilience in such a context implies taking into consideration engineering and organisational aspects both related to constituent systems and the overall SoS level. In our study of SAR operations, reflecting crisis management, the need for dynamic responses, flexibility but also safety, it was prevalent that resilience is connected to a range of available constituent systems executing a diversity of tasks, complementing each other on a SoS level to execute a mission. Further, it also emerged that resilience in CoIS relies on the use of a range of organisational as well as system approaches.

Second, the study revealed the double-edged sword of the use of AI and AS. It appears that, on the constituent systems level as well as on the SoS level, AI and AS can contribute to system capabilities and resilience in several ways (e.g., improved situation awareness, performing tasks that are dangerous, quick deployment of resources) but also hamper resilience (e.g., through confined operational envelopes). This both-and effect on resilience creates a need for a new understanding of resilience, taking into account the constituent system and the SoS-level perspective. It reflects the irony of AI (Endsley, 2023), as it creates new challenges, but also possibilities, for human interaction and how resilience can be achieved.

Third, in future CoIS, reflecting SoS with AI integration, it appears that there is a need to create a balance between AI/autonomy and human-operated systems so that systems can combine human expertize and AI capabilities, and remain flexible, adaptive, and responsive when a broader understanding and reasoning is needed. This is especially prevalent in unpredictable scenarios that cannot be fully planned and understood beforehand.

Theoretically, the transition to CoIS opens a broad landscape for researchers to explore (Lakemond et al., 2024; Yu et al., 2024), not the least related to contingencies and crisis management. In this paper, we studied the domain of SAR at sea, which serves as a rich source of insights into the advancement of CoIS, organisational as well as engineering perspectives on resilience, including the preparation for situations that extend well beyond conventional emergency response scenarios, and not the least when nontrivial relations between organisational and engineering perspectives potentially plays an important role for resilience (as shown in Figure 5). While this domain has its peculiarities, it may also serve as an example and reflect developments related to other complex and increasingly intelligent systems, like transportation networks or energy systems.

In the research design section, we emphasized the uniqueness of our case, which closely mirrors actual SAR operations, and to mitigate bias in our analysis, we aligned our interpretations with a triangulated approach. However, we acknowledge certain limitations in our study. While our data collection and analysis were conducted qualitatively based on the unique case of WARA-PS aiming for future relevance, we call for future research to develop models and conduct in-depth comparative analyses with quantitative methods. This would help identify patterns and complement our work, further highlighting the role of artificial intelligence.

Future studies can advance the insights provided in this paper by extending them to other domains and delving deeper into specific areas, such as safety and reliability culture (Cantu et al., 2020). These explorations could further contribute to the emerging CoIS. Additionally, future research could also explore new approaches, like bounded generativity, to manage increased generativity across different system levels, while still fulfilling systems' overall criticality needs, one way suggested as key to mastering CoIS (Yu et al., 2024).

Lastly, the introduction of AI regulations, such as the Blueprint for an AI Bill of Rights in the US and the EU AI Act, highlights the importance of compliance and certification in AI system development and deployment. The Blueprint for an AI Bill of Rights provides "*principles and associated practices to help guide the design, use and deployment of automated systems to protect the right of the American public in the age of artificial intelligence*" (p. 4).[11] Similarly, the EU AI Act focuses on regulating the development and use of AI systems, particularly those classified as high-risk (Art. 6(1),[12] Art. 8).[13] Also, the providers (developers) of high-risk AI systems must comply with certain requirements, such as establishing, implementing and maintaining a risk management system (Art. 9),[14] data governance practices (Art. 10),[15] being transparent to provide information of risks in foreseeable circumstance, among others (Art. 13),[16] as well as including human oversight measures to prevent or minimize risks (Art. 14).[17] These regulations have highlighted the necessity of incorporating compliance considerations into AI system application process, and the growing emphasis on compliance suggests that the issue will continue to be explored and refined in future research.

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CONFLICT OF INTEREST STATEMENT

This work is funded by the Marianne and Marcus Wallenberg Foundation. The case studied is part of a large research programme funded by another Wallenberg foundation, the Knut and Alice Wallenberg Foundation. Neither of the funding agencies has been involved in the case selection and design, execution, or in defining the outcomes of our study. One of the authors has been involved in setting up the research arena that was part of the studied case and has been imperative for gaining access to and forming a deep understanding of the studied case in its context, including the rationale for setting up the arena. He does not gain personally from publishing the case of WARA-PS. Measures have been taken to avoid potential bias, for instance including involving a variety of informants, direct observations by the other two co-authors, publicly available secondary material, and analyses that were performed independently before merging into a case description.

DATA AVAILABILITY STATEMENT

The secondary data regarding search and rescue operations at sea in Sweden, WARA-PS, and its demonstrations that support the findings of this study are openly available through publicly accessible links provided in the footnotes or Research Design section in this manuscript. The participants and interviewees in this study did not consent to public data sharing, due to restrictions of external access, and to protect their privacy, supporting data from observation notes and interview transcripts are not available.

ORCID

Youshan Yu http://orcid.org/0000-0002-4966-4620
Nicolette Lakemond https://orcid.org/0000-0002-5427-3560
Gunnar Holmberg https://orcid.org/0000-0002-8338-0218

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APPENDIX A: DESCRIPTION OF INTERVIEW OUTLINE

During the annual demonstrations' workshops, eleven unstructured interviews were performed as well as a number of informal conversations with the participants. The interviews were performed with key participants, such as representatives from the Swedish Sea Rescue Society, the project manager, coordinators responsible for developing SAR scenarios as well as other contributors to the demonstrations. The respondents were all selected due to their deep involvement in the design of WARA-PS as well as the execution of the demonstrations. The interviews were unstructured, that is, they did not follow a clear outline with predetermined questions. Nevertheless, a protocol with themes was followed and data was captured on several themes. The initial interview outline consisted of the following themes:

- The vision, strategy, actors and organisational context of WARA-PS
- The organisation, including core team and the actors' role in WARA-PS
- The setup of the core system as well as other (constituent) systems, services and agents used in WARA-PS
- The development and evolution of WARA-PS
- System integration
- System properties, for example, safety, generativity
- Resilience
- System boundaries, including new capabilities, actors
- Decision-making and delegation
- Design of scenarios
- Collaboration between industry and academia

Throughout the interviews and conversations, also specific issues related to, for instance, design initiatives, areas of interest, participants' experiences, technical prerequisites, capabilities, scalability, perspectives on the future of AI and autonomous systems (in SAR), and societal challenges were brought up and captured.