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AI in the Context of Complex Intelligent Systems: Engineering Management Consequences

Youshan Yu, Nicolette Lakemond, and Gunnar Holmberg

***Abstract*—As artificial intelligence (AI) is increasingly integrated into the context of complex products and systems (CoPS), making complex systems more intelligent, this article explores the consequences and implications for engineering management in emerging complex intelligent systems (CoIS). Based on five engineering management aspects, including design objectives, system boundaries, architecting and modeling, predictability and emergence, and learning and adaptation, a case study representing future CoIS illustrates how these five aspects, as well as their relationship to criticality and generativity, emerge as AI becomes an integrated part of the system. The findings imply that a future combined perspective on allowing generativity and maintaining or enhancing criticality is necessary, and notably, the results suggest that the understanding of system integrators and CoPS management partly fundamentally alters and partly is complemented with the emergence of CoIS. CoIS puts learning and adaptation characteristics in the foreground, i.e., CoIS are associated with increasingly generative design objectives, fluid system boundaries, new architecting and modeling approaches, and challenges predictability. The notion of bounded generativity is suggested to emphasize the combination of generativity and criticality as a direction for transforming engineering management in CoPS contexts and demands new approaches for designing future CoIS and safeguard its important societal functions.**

***Index Terms*—Artificial intelligence (AI), complex intelligent systems (CoIS), criticality, engineering management, generativity.**

I. Introduction

INTELLIGENT technologies driven by solutions using artificial intelligence (AI) are currently regarded as having great transformative potential to achieve new valuable outcomes [1]. AI solutions, despite still being relatively limited, have started to emerge in a wide variety of industries and sectors, including, for instance healthcare, transportation, cloud-based systems, aviation, and power supply. Such inclusion of AI solutions induces new disruptive characteristics to existing management and innovation practices [2] and needs scholarly attention for outlining implications and consequences.

Despite an increasing interest in AI, few scholars have yet put in the foreground that many of the potential benefits of AI solutions will emerge in a dynamic context in which they are used and implemented. At the same time, an understanding of the consequences of AI is highly intertwined with an apprehension of contextual characteristics [3]. In current contemporary research, the potential of AI is often studied and considered in connection to standalone applications [1], [4] and single aspects, such as data governance [5], rather than considering AI solutions in their context. In addition, many contributions are still on a conceptual level, outlining perspectives on future decision-making [6], innovation management [1], [2], and the broader management domain [7]. Empirical studies are still relatively scarce. Given AI solutions emergence in complex context, attention to the use of AI solutions in the complex products and systems (CoPS) in which they emerge would potentially provide additional insights into understanding consequences and implications for management in general and engineering management in particular [8].

CoPS have specific characteristics, at least in comparison to mass-produced goods. They require distinctly different ways of organizing innovation processes, system architectures, and system integration capabilities [9], [10]. Over the last few decades, CoPS have transformed into digital–physical systems with an increasing role of electronics and software to achieve critical functionality [11]. At the same time, CoPS are becoming increasingly generative, i.e., they are emergent in character and display an inherent and recursive growth in diversity, scale, and embeddedness [12]. Generativity is related to a system's ability to create new output without input from the originator of the system [13], and often beyond initially foreseen usage of the system. This is not least visible in the increasing importance of system of systems (SoS) that represent a collection of dedicated constituent systems working together forming a new, more complex system offering more functionality than simply the sum of the constituent systems. When AI is becoming an integrated part of these systems they transform into, what can be referred to as, complex intelligent systems (CoIS) [8]. Such systems maintain many of the characteristics of CoPS but contain increasingly intelligent content that changes the nature and management of these systems.

Building on a central challenge in contemporary CoPS, namely the quest to combine the merits of system generativity

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Youshan Yu is with the Department of Management and Engineering, Linköping University, 581 83 Linköping, Sweden (e-mail: youshan.yu@liu.se).

Nicolette Lakemond is with the Department of Management and Engineering, Linköping University, 58183 Linköping, Sweden (e-mail: nicolette.lakemond@liu.se).

Gunnar Holmberg is with the Department of Management and Engineering, Linköping University, 581 83 Linköping, Sweden, and also with the Saab AB, 581 88 Linköping, Sweden (e-mail: gunnar.holmberg@liu.se).

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and the need for safeguarding system criticality [11], the purpose of this article is to explore engineering management consequences following the inclusion of AI in the context of complex and increasingly intelligent systems. The article addresses particularly the implications of a combined focus on generativity and criticality and outlines the consequences for CoPS management.

Generativity has been associated with increasingly digital solutions in CoPS [14] and is related to, for instance, scalability and pace of innovation, and a wide range of actors that contribute to the system [15]. In contrast, criticality is related to system properties, such as safety, security, and reliability [16], [17] and rather strict and control by a core organization (i.e., traditionally often system integrators) as well as adherence to standards, certification, and guidance by regulatory bodies [10], [16]. Although generativity and criticality are often perceived as widely disjunct and contradictory aspects, it seems that they can be addressed simultaneously through a combination of organizational, architectural, and management choices in engineering management [11]. They are also becoming inseparably intertwined as generative solutions are increasingly crucial for improved safety and reliability [8].

A better understanding of how generativity and criticality can be addressed in the face of the emerging integration of AI solutions may provide important steps forward toward successful AI inclusion in complex systems, mitigating the concerns that have been raised related to trustworthiness, reliability, and safety [18], [19], [20]. Based on five aspects that reflect engineering management concerns in complex systems, including aspects related to design objectives, system boundaries, architecting and modeling, predictability and emergence, and learning and adaptation [10], [21], [22], [23], this article outlines the implications of AI inclusion in CoPS. A case study of a research demonstration arena in the field of public safety that aims to enhance knowledge on the future use of AI and autonomous systems illustrates how these aspects play out in a real-world use context.

In the next section, the theoretical background connected to the context of complex systems and the emergence of CoIS are further described. Particular attention is given to outline the five aspects, including their focus on system generativity and criticality. This is followed by a description of the research methods employed in this article. The results section provides a general overview of case as well as the major findings in relation to the five aspects. These findings are analyzed and compared to current knowledge on engineering management and CoPS literature in relation to the five aspects, the combination of criticality and generativity as well as the overall implications of the transition from CoPS to CoIS. Finally, the conclusion section outlines the major contributions and insights from this article, their implications for theory and practice, limitations, and several avenues for further article.

II. Theoretical Background

A. From Complex Systems to Complex Intelligent Systems

While AI is increasingly discussed as being able to incrementally advance CoPS, e.g., based on continuously combining and analyzing multiple data sources and creating new or supporting functionality [2], understanding its impact is challenging. Typically, the qualities or behaviors of complex systems are not as simple to aggregate as the qualities and behaviors of the underlying constituent systems that form a CoPS [24].

Complexity in CoPS refers to a high number of nonstandard components and subsystems and reflects the breadth of knowledge and skills required, and the extent of new knowledge that is needed in development and production [25]. Complexity involves not only the traditional technical aspects of design but also the requisite organizational and management processes [26]. With the inclusion of AI technologies, and thus an increasing intelligence in complex systems, complexity typically does not only evolve around rather stable system characteristics but is increasingly also affected by system generativity of the overall CoPS as well as of its constituent systems in an SoS context. Such generativity refers to system behaviors and functionality that often cannot be foreseen and are beyond a system's original intended scope. Generativity builds on the characteristic that resources and their recombination maintain open to new diverse and complementary outputs both in the system as well as through contributors to the system [2], [13], [27]. Generativity is tightly related to scalability properties that are associated with AI solutions, a constant pace of innovation and reconfiguration capabilities. Therefore, as systems evolve during their lifetime, and generativity becomes increasingly important, also system complexity becomes a more dynamic property over time.

Complex systems have received considerable attention from the late 1980s and onwards. Complex systems have been studied in multiple perspectives both in relation to products (e.g., flight simulation and medical devices) and infrastructures (e.g., telecom and energy systems), such as in the literature on CoPS [9], [28], large technical systems [29], high reliability organizations [30], and normal accident theory (NAT) [22]. Several of these streams in the literature sprung out of concerns related to catastrophic events in high-risk systems, such as the explosion of NASA's spaceship Challenger in 1986, the nuclear reactor accidents at Three Mile Island in 1979, Chernobyl in 1986, the chemical plant disaster in Bhopal in 1984, and aircraft and marine accidents. This put the issue of system criticality high on the agenda. NAT brought forward an understanding criticality in relation to system architectural aspects [22], while other studies have stressed resilience aspects in managerial approaches and organizations [30], [31] or pointed at the embeddedness of such systems in a broader context [29]. Despite a somewhat dystopian view on accidents at the time [22], remarkably few accidents have occurred during the past 30 years. This is particularly noteworthy given society's increasing reliance on complex systems infrastructures. New managerial and organizational capabilities as well as increased use of digital control systems have probably played an important role in safeguarding system criticality [11], [31]. This is for instance evident in contemporary practices in systems engineering involving organizational arrangements and routines, the use of a variety of model-based approaches, simulation, and architectural approaches [26].

System integration has been considered one of the core capabilities of system builders [32]. A focus on system integration has evolved from military, engineering-based origins into a

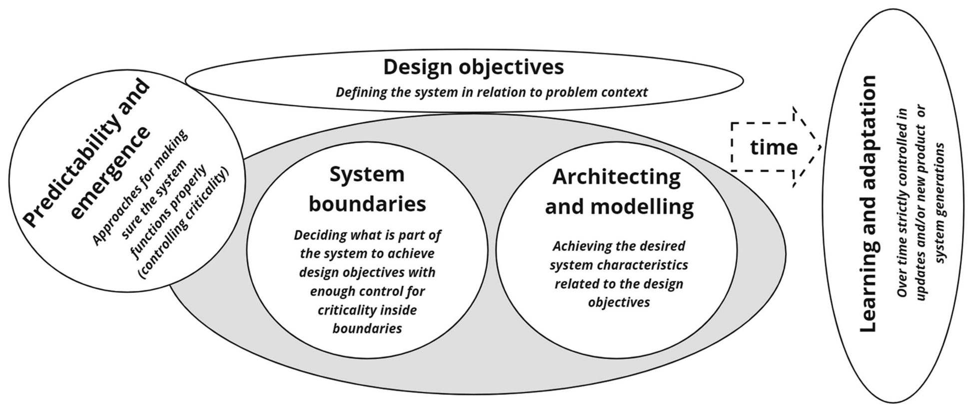

Fig. 1. Five aspects and their current engineering management logic in complex systems.

capability that reflects system builders' embeddedness in a larger network of firms engaging in simultaneous processes of vertical integration and disintegration [21]. The more complex, high-tech, and high-cost the product, the greater the system integration challenges [21]. Modern complex systems, such as cars and aircraft, comprise physical, digital, and legislative artifacts and involve more than one single organization [11]. Often, multiple technologies and functionalities are involved, intertwined, and could perhaps interact in unknown and unforeseen ways.

With the introduction of AI as an integrated part of complex systems [8], i.e., a shift from narrow AI doing a specific task [33] to embedded AI performing a range of interdependent tasks, the challenges related to CoPS design may alter. The introduction of AI may reinforce learning, autonomy, and adaptability characteristics of CoPS [6], [34] and potentially expands the set of possible emergent behaviors. Rather than designing a system according to traditional approaches, i.e., based on the functional requirement, "hierarchical, top-down design" [35], and finding corresponding solutions, the focus of future development of CoPS may be on creating trainable data-driven partitions of the system. With the addition of intelligent technologies, CoPS are also increasingly evolving into SoS, characterized by goal sharing and lose couplings among its rather independent constituent systems performing specific tasks to provide larger complex functionalities [36], [37], [38], [39] and changing the prerequisites for management [38], [40], not the least in relation to criticality and generativity.

B. Engineering Management Aspects of CoPS Design

Many of the contemporary grand challenges societies are facing, for instance, related to healthcare, infrastructure, environment, and security, are emerging, and addressed in the context of complex systems. These systems are "…large numbers of interacting elements. There are many attributes of interest and many stakeholders, who often have differing objectives and needs. With these many stakeholders acting and reacting, the response of these systems can be unpredictable with phenomena emerging that could not have been anticipated." [23, p. 261]. The management issues are multifaceted and dynamic. These characteristics can only be expected to be reinforced in currently emerging CoIS. With the integration of intelligent solutions, previous perspectives on CoPS will thus expectedly need to be expanded. Several aspects of contemporary complex systems have been brought forward by Rouse [23], and are also represented in the CoPS literature [10]. Aspects related to design objectives, system boundaries, architecting and modeling, predictability and emergence, and learning and adaptation during the evolution of systems are central to understand engineering and management challenges of CoPS design. These are shown, including the current engineering management logic in complex systems, in Fig. 1, and further described below.

First of all, the *design objectives* relate a system to its problem context and define the system [23]. They are related to an identified need that the system is intended to respond to and translate into system requirements [41]. Design objectives involve the consideration and balancing of conflicting requirements and selecting the content of the system enabling a value that is typically beyond the sum of components. This requires that multiple perspectives are taken to cover important considerations related to product quality, market, cost, robustness, and security. A multitude of perspectives facilitates in making appropriate tradeoff and finding a set of decision criteria and alternative courses of action in the design process [42]. The nature of the design objectives is directly related to system criticality as the related choices and tradeoffs determine how well the system will be able to perform its function and resist disturbances. Traditionally, related to the design objectives, generativity has got less attention in the engineering process.

The *system boundaries*, as a second dimension, can be understood by considering the system in its context [23]. The definition of system boundaries is a fundamental part of the design of complex systems. It is an activity that basically refers to an understanding of what the system is (and what not). System boundaries have been associated with the possibility to achieve the design objectives, but also with the authority to allocate resources, the incentives that can be created to contribute to a system, and control in general [23], [43]. Too broad boundaries imply that little of the system can be directly affected but too narrow boundaries could result in a system that does not respond to important contextual elements [23]. In the context of complex systems, the system boundaries also define the stakeholders that are involved, such as customers, suppliers, governmental authorities, policy makers, etc. Each of these stakeholders have somewhat different objectives and needs which all need to be managed throughout the engineering process [9], [44]. In complex system engineering, the traditional logic related to system boundaries is one of control inside the boundaries, where control is deemed necessary to achieve system criticality [8].

Third, *system architectures* are means to achieve the desired system characteristics and are central for addressing growing complexity [23]. Architectures help to make performance tradeoffs, enable new levels of integration, and may facilitate opening up for novel functionality [45]. A system architecture reflects the structure of the system and its relationships and requires a deep knowledge of the overall architecture as well as the components in the system in the engineering process [23], [46], [47], [48]. In contemporary practice, modeling approaches contribute to evaluation, experimentation, and may support a project team's ability to create a shared understanding of the common task [8]. Traditional system architectures for complex systems have mainly focused on building enough control for system criticality into the system, although new architectural approaches enabling generativity have started to emerge [11].

Although *predictability and emergence*, as a fourth dimension, basically could have indicated some kind of generativity, contemporary practices have rather outlined the relationship to criticality. Predictability and emergence have been associated with phenomena and events that cannot be fully foreseen but may have important consequences for the system's functioning [23]. Such events can even have severe implications when accidents are caused by system failures [22]. To mitigate this, organizational approaches including a mindset focusing on being sensitive to early signs of failure, avoiding simplifications, commitment to resilience, and deference to expertise have been found important for managing unexpected events [30], [31]. In addition, traceability has been important in industrial engineering management practice [49]. Therefore, it seems that predictability and emergence focus on controlling criticality rather than allowing for generativity through a focus on making sure that the system functions properly under different circumstances. The contemporarily logic thus implies that predictability and emergence, as an aspect in engineering management, bridge the design objectives and how these are implemented through the system's boundaries and architecture.

As a fifth dimension, and perhaps mostly connected to generativity, *learning and adaptation* are important characteristics of complex systems. The structure and dynamics of systems may change over time and may make important tradeoffs between, on the one hand, more flexible systems and, on the other hand, rather static optimized systems that are only robust within the operating conditions [23]. Often, systems are updated in several generations, with a certain purpose, such as improving performance, or adding new features [8]. Learning and adaptation exhibited during the evolution of the system allows for a system to transform, address new objectives, and operate in new contexts [23], all indicators of generativity. However, such generativity seems to be rather controlled over time through updates and/or the launch of new generations of the system at certain points in time.

While the current logic related to the five aspects reflect CoPS engineering management, the fast-approaching inclusion of intelligent technologies expectedly alters several of the aspects. This may have important implications for engineering management as a discipline and CoPS management in particular, not the least if the fundamental nature and focus of the aspects in relation to generativity and criticality transforms and/or expands. This is further explored through an empirical exploration in the next sections.

III. Research Method

A. Research Approach, Data Gathering, and Analysis

To explore the changing characteristics of engineering management in emerging CoIS, we have actively searched to find a context that represents such a system. As the implementation of intelligent technologies is not widely spread yet, at least not as an integrated part of CoPS [8], we opted to study a real-world representation of such an emerging system. This representation is set within the context of a large research initiative, namely Sweden's WASP program for AI and autonomous systems research. Within this program, we could study one of its research arenas, the WASP Research Arena in Public Safety (WARA-PS), which is demonstrating search and rescue (SAR) scenarios. It has been described as "A research arena (WARA-PS) for sensing, data fusion, user interaction, planning and control of collaborative autonomous aerial and surface vehicles in public safety applications…" with the intention to "demonstrate scientific discoveries and to generate new directions for future research on autonomous systems for societal challenges." [48, p. 1]. As a research-based endeavor, WARA-PS represents the emergence of future CoIS, where AI-based solutions play an integrated role, and creates a context in which surface vehicles, drones, underwater vehicles, and people can work together in a unique way, building on a collaboration between researchers in the WASP program and industry partners. Studying this unique context may not only provide an understanding of the research arena itself, but also about broader future engineering management implications for CoIS.

Our overall research aims at understanding and envisioning the consequences of AI and autonomous systems and thereby contributing to shaping the desirable outcomes of AI, i.e., contributing to responsible and purposeful innovation [51]. The research reported in this article adopts a case study method [52]. It focuses on understanding consequences and strategies of CoIS before their actual implementation [3], while still anchoring our findings in empirical observations.

We have been able to follow WARA-PS since it was designed as a research instrument in 2016. As part of an ongoing process study, primary and secondary as well as participatory and observational data have been gathered continuously throughout almost 6 years. One of the authors has been deeply involved in the set-up of the research arena and has detailed insight into the principles, strategy, and rationale behind the arena. Throughout the years, the authors have participated in the activities connected to the research arena, including five successive yearly demonstration workshops starting 2018 and the latest 2022. Roughly 67 h of observations were documented during these demonstration workshops, including numerous informal discussions with the participants. In addition, approximately 9 h of interviews were performed with key informants, including the project manager, one of the initiators of the arena (currently sponsor and coordinator), the business analyst, industrial representatives, and several participating Ph.D. students. A considerable amount of secondary data were collected from the WASP website,[1] WASP conference presentations, cooperation plans, WARA-PS resource portal,[2] project documents, etc.

Data analysis has been ongoing throughout the years. The emerging understanding related to the management aspects, generativity, and criticality was based on content analysis of the material [53], as well as writing up a case study report focused on the evolution of the research arena, its activities, and outcomes. A structured analysis was performed, focusing on the five aspects and their indications based on the theoretical framework. For instance, related to the design objectives it was searched in the data that reflected the overall objective, mission, ultimate goals, not only in one point in time, but also how the formulation of the design objectives changed over time. This in-depth analysis has resulted in a deepened understanding of these aspects, their relationship to criticality and generativity, as well as typical supporting quotes for the empirical findings. The findings in relation to the management aspects were abstracted from the case study report as well as based on the categorized reflection of the material. Continuous and regular discussion with the project manager and other key informants contributed to the validation of the findings.

B. WARA-PS Research Arena

The purpose of the WASP research arenas is to enable research to be conducted outside a lab environment and with close industrial connections and support resources. The ultimate goal is to facilitate bridging the gap between scientific research and industrial applications and allow for a research context well beyond what can be achieved by individual research labs [50]. The research arena functions as a system-level platform in which data, new knowledge, and research directions can be created and explored. A multitude of actors is involved, including the WASP research community and industrial firms like Saab, Ericsson, Axis Communications, and Telia, and public organizations like the Swedish Sea Rescue Society (SSRS). Throughout the years, the community of stakeholders has grown and is now including Swedish governmental agencies as the Swedish Maritime Administration, Civil Aviation Administration, Police Authority, Swedish Defence Material Administration, Swedish Armed Forces, and Swedish Defence Research Agency.

The arena supports the execution of a variety of scenarios by integrating industrial and academic lab systems into a complex system-level demonstration. Such a demonstration takes place every year in the city Västervik on the Swedish east coast, with additional field tests in May as well as based on request by the different research groups. Unmanned vehicles (e.g., surface vessels, underwater robots, and drones) as well as manned vehicles (optionally autonomous vessels) collaborate in a predesigned scenario, resulting in new insights, data, but also new research directions.

The research arena is continuously supported and coordinated by a core team of people working together with additional research engineers and researchers. The core team meets every week for planning and reviewing progress. Additional integration meetings take place regularly to expand and integrate new services and to make sure that a core system is kept up and running online continuously.

Technically, the research arena is made up of a core system that is domain agnostic and always available for, e.g., integration tests. The main goal of the core system is to facilitate research that focuses on collaborating autonomous agents. It enables an infrastructure for system research including a variety of agents, systems, and services, and includes a mix of simulated and physical systems that can be integrated, reconfigured, and shared into a common overall system. An overview of the overall core system is shown in Fig. 2. The overview is schematic and shows the feedback loops to connect the different systems, including autonomous mission planning on the right and AI data collection on the left that is described in 5-year evaluation report[3] as to "form an autonomous SoS with human in the loop."

IV. WARA-PS and the Five Engineering Aspects

A. Nature of the Design Objectives

The design objectives of WARA-PS are focused on demonstrating SAR scenarios, progressively during several years, to obtain insight into future design and management in CoIS. The research arena's focus is on collaboration between humans and autonomous SoS. The arena is operating across several domains, including air, sea, underwater, land, space, and cyber. Its design objective is related to public safety missions, in particular, SAR scenarios. The selected scenarios represent a challenging environment with unforeseen events, including incompletely defined missions where an evolving understanding and resource availability are critical. The context of SAR represents these characteristics, but a more general design objective is related to creating an understanding of situations well-beyond the scenarios that are demonstrated. It is noted by the key stakeholders that this includes possible transferability of the gained understanding to other critical systems or infrastructures that also may be subject to unforeseen events. According to the evaluation report, it is described that *Multi-domain and mixed scenarios are one of the keys to stimulate research challenges, concept development and to learn from results in other domains.*

WARA-PS is thus set-up as a more general arena to learn beyond SAR, including solving safety and security issues in other domains. According to the CTO of one of the industrial partners: *WARA-PS is an excellent way to bring together the*

[1] [Online]. Available: https://wasp-Sweden.org
[2] [Online]. Available: https://portal.waraps.org/about
[3] [Online]. Available: https://strapi.waraps.org/uploads/WARA_PS_katalog_a20b77ff9c.pdf

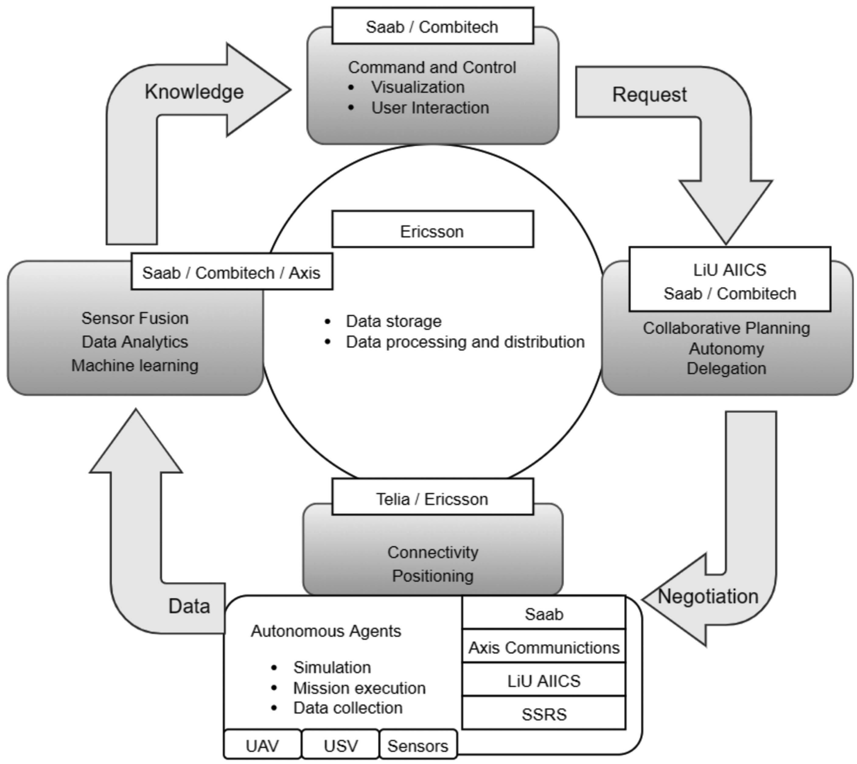

Fig. 2. Overview of the system (adapted from WARA-PS internal presentation material).

cutting-edge research of the academia with the needs of the government and challenges for the industry. By executing WARA-PS, we are creating consensus about which problems need to be solved, and how to best solve them by working together. We can thereby make sure that we are all working in the same direction. WARA-PS hence becomes a creative innovation platform….

As part of the design objectives, the core system is designed with flexibility in mind. This is described in the internal documentation as *This means that the Core System Infrastructure shall enable different agents, systems and services to be integrated and shared in a common overall system. It shall also be easy to take advantage and contribute to the system.*[4]

Notably, there are multiple views of the objectives of each application as subset of the whole arena. The system has emerged into a recombination toolbox and the complete arena includes application-specific add-ons that can be tested and explored within the arena. The system's design objectives have changed over time based on stakeholder needs, emerging ideas and more challenging conditions. For instance, the project manager explains: *I mean to create really interesting research on the data sets we need to, for example, fly in wider areas where you can't see the vehicles.* This in turn may create new challenges in relation to operating the system in an increasingly complex and regulated environment, implying the need to consider more aspects.

In the 5-year evaluation report, the focus of WARA-PS over the years is described as follows:

[4][Online]. Available: https://strapi.waraps.org/uploads/WARA_PS_Core_System_Infrastructure_v_1_3_9d55e76731.pdf

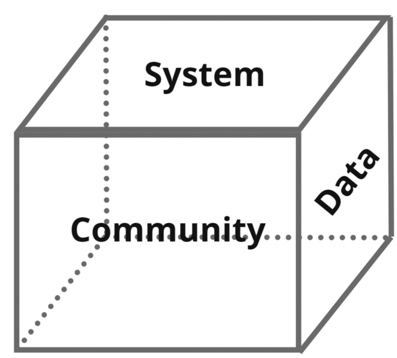

Fig. 3. Design objectives focus on system, the community, and data.

2016—Prestudy and definition
2017—Starting activities
2018—First system demonstration
2019—Expanding the community
2020—Multidomain data collection
2021—Established system, triple helix, and wider scope

This implies that, over time, the design objectives have reflected different dominant perspectives, including successively, the system, the community, and data (see Fig. 3). WARA-PS strategy has also changed and has increasingly involved related projects from different domains. This is explained in the 5-year evaluation report as follows: *In 2021 we changed strategy and tried to find public safety related projects in definition phase or recently started that had need for real data and challenging environments.* and "*…datasets have been collected at events to*

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bring the reality into models for development and simulations in the lab/desktop. There is a data collection process developed and used. However, each project has specific needs, which implies that there is work to be done to offer a general and efficient data collection process. There is a lack of relevant datasets containing annotated video and images with corresponding movement tracks and user behavior to be used for public safety research.

Despite a changing focus in WARA-PS over time, the plan for the coming years includes an overall problem area that was part of the original definition stage of the arena. The overall objective is formulated within the context of *Collaborating humans and autonomous systems of systems with intense interactions and sliding combinations of human authority and systems autonomy.* It is also noted that there is an increasing interest, nationally and internationally, to use WARA-PS as a test bed. It is planned for a new generation of WARA-PS that covers a wider scope but that still operates to expand knowledge on collaborating autonomous systems.

B. System Boundaries

While the core system serves as an infrastructure for testing and data gathering, it is based on important principles including domain agnostic, easy integration, available 24/7, and transparent and accessible. It has over time grown to involve more systems and include heterogenous agents including human beings. As a reconfigurable infrastructure for system research, it can involve different agents, systems, and services.

Several important stakeholders are involved in the arena, including industrial actors, the SSRS, governmental agencies, the WASP research community, as well as additional research centers (e.g., the Swedish Maritime Robotics Centre focusing on under water research).[5] A representative of the SSRS explains their interest: *WARA-PS is an exciting opportunity for us to connect with top researchers and companies that develop advanced technologies and to influence work in fields that may one day help us save lives in new, efficient ways.*

Over time, the number of stakeholders and their interests have grown, and the boundaries of the system have become more fluid in terms of the components and subsystems of the system, the actors involved, and the focus of the system. In the 5-year evaluation report, it is expressed that *…we now have brought together projects from multiple domains with shared research interest.* Specifically, data gathering and sharing have become increasingly central, and WARA-PS is sometimes referred to as a "data factory." The core system, functioning as a state-of-the-art research infrastructure, is made available to allow testing and data gathering.

On the WARA-PS website,[6] a list of systems used for data collection, test development, and demonstrations is provided including the following:

1) One Combat Boat 90.
2) Four quadcopters with EO/IR sensors.
3) Two USVs—Pirayas.
4) A fixed-wing small plane.
5) Sensors like cameras, LIDAR, and sonar mounted on the vehicles.
6) Computer and storage resources in the cloud.
7) A command-and-control system for human interaction.
8) A delegation framework for collaboration between the systems.

There is still an ambition to evolve the focus of WARA-PS and extend the boundaries as explained by the project manager "we have done some experiments and we're happy with the results, but then we want to do wider experiments and then we need to extend the boundaries and so …"

C. System Architecture

The approach to the system architecture in WARA-PS focuses on enabling a flexible integration through recombination of existing and new systems and platforms (see also the list systems above) and increasingly novel functionalities. The architecture includes heterogeneous autonomous agents (vehicles and sensors), command and control (C2) functionality at different levels with varying degrees of human authority and AI, communication, and cloud computing services (see representation of the overall core system in Fig. 2). The core architecture of WARA-PS is expandable and scalable by incorporating additional heterogeneous autonomous systems and new public safety ideas [50].

In addition to the core system, a resource portal[7] serves as "…a platform and guide, helping users to locate the information, dataset or tool needed. Via the portal the online storage space for media and data is accessible" (5-year evaluation report).

Within each subsystem's domain, the actors have their own modeling approaches. During demonstration, they reach a synthesis with specific complementary procedures to make sure that the system works in a coordinated way. Through the resource portal, a description of the core system infrastructure can be found.[8] Tutorials are available describing the execution environment through which the system can be tested and missions can be simulated. For the core systems to function together, an application programming interface (API) is implemented.[9] The API reflects several design decisions related to the architecture, including the use of regular heartbeat messages sent by human or robotic agents. Such heartbeat messages allow, for example, for registering the availability of the agent to the rest of the system. Whenever the communication is requiring a response, it is decided that it should be asynchronous. For identifying a communication message, a universal unique identifier (UUID) is used. Also, the event of unreliable communication can be handled through a procedure including resending commands with the same UUID until it is given up or a response has arrived.

[5] [Online]. Available: https://smarc.se

[6] [Online]. Available: https://wasp-Sweden.org/research/research-arenas/wara-ps-public-safety/

[7] [Online]. Available: https://portal.waraps.org/

[8] [Online]. Available: https://strapi.waraps.org/uploads/WARA_PS_Core_System_Infrastructure_v_1_3_9d55e76731.pdf

[9] [Online]. Available: https://strapi.waraps.org/uploads/waraps_api_752c93d889.pdf?updated_at=2022-10-04T12:31:43.216Z

The core architecture of systems is thus complemented with predefined procedures to guarantee safety and criticality issues. Basically, these are focused on ensuring that the different parts of the system run together safely in an heterogenous environment. According to the project manager: *We have different organizations working together and they have completely different methods of describing and modelling a system and so we are in a mix of on the one hand very generative because we have this very prototype stage of systems, and then on the other hand we have this safety related perspective also in the designed model. We want to model and have a very clear view of how the system performs….*

D. Predictability and Emergence

Predictability and emergence aspects are not only focused on extensive risk analyses but managed through replanning and reallocation possibilities ready in case contingencies would emerge. As described above, the capability to be able to deal with unforeseen events is an integrated part of demonstrations. *The goal of showcasing realistic scenarios is to put the technology and systems in a representative and interesting context, with unforeseen events and a changing environment* (5-year evaluation report).

A focus on criticality is partly achieved through the system architecture and set-up. However, to ensure safety, also higher level general responding procedures have been set-up. For instance, the design decisions and procedures in the architecture include that execution can be suspended when an unsafe situation occurs. Execution can be resumed when the unfavorable conditions disappear and the situation returns to normal operational conditions. Such execution replanning can be done autonomously or by C2 interruption through human intervention. C2's control level varies depending on the system's maturity and autonomy. C2 also has the most authority to command all agents within the communication range or the option to end execution in higher level general contingency management. This is explained by the 5-year evaluation report as follows: *This approach addresses scenarios deviating from the normal, focusing on incompletely defined missions with evolving understanding and resource availability. The types of scenarios are expected to cover situations well beyond those demonstrated, e.g., the ability to deal with deviations in many critical infrastructures such as power supply and transport systems (weather, accidents…).*

E. Learning and Adaptation

WARA-PS was made for learning and adaptation, and not surprisingly, learning and adaptation are an inherent part of all engineering management aspects. The system is not only flexible, scalable, and reconfigurable, but has also in its focus continuously evolved. The activities have changed from initially setting up the arena and the system, to creating the community around the system and more lately into focusing on data collection and infrastructure building for knowledge distribution. According to the project manager of WARA-PS, this evolution reflects the research arena and CoIS' learning and adaptation. *The research focus has been the same on a high level during the years of arena operation, but the research topics and content of the arena varies to adapt to ongoing projects, activities of researchers, industry interests and cluster activities.*

In a way, the research arena has served as an arena for learning and achieving the mission to create an understanding of collaborative autonomous systems that are increasingly having intelligent content and its implications for society. This is explained in the 5-year evaluation report as follows: *It has now broadened to include more use cases applicable in more scenarios, such as traffic management, surveillance, transportation in smart cities, forest protection, more dynamic search, and rescue missions, etc. The scenarios are used to display the capabilities of the WARA-PS systems in a way that could be useful in society. Lessons learned and research results are applicable also to a wider range of applications and domains through similarities and analogy. Scenarios also bridge the gap to real users.*

The ambition is to continue to learn and adapt the arena into its next generation: "The next three years, the arena could expand to a "WARA-PS 3.0," covering a wider scope with more partners, scenarios and systems, still focusing on collaborating autonomous systems in real world scenarios with unforeseen events" (5-year evaluation report).

V. Analysis and Discussion

An analysis of the five engineering management aspects indicates that the landscape for engineering management partly alters fundamentally but also complementary to cover a wider scope. This, in turn, has consequences for CoPS management and the changing role of CoPS integrating firms along with the emergence of CoIS. First, the main implications in relation to the five engineering management aspects are analyzed and discussed, followed by a discussion on the accentuated tension between criticality and generativity in CoPS management and the new landscape for CoIS management including the changing role of system integrating firms.

A. Analysis of Engineering Management Aspects in CoIS

The findings from the case study of WARA-PS indicate a partly altered and partly complemented understanding of engineering management related to the five aspects.

First, in CoPS, design objectives are usually rather clearly defined in relation to what problem the system, subsystems, and components are supposed to address or solve [23]. Traditionally, as also put forward in the CoPS literature, leading systems firms take on the role of system integration, including the main task of designing and strategizing the future development of the CoPS [21]. This includes a long-term dominating influence on the design objectives. In relation to this, the findings show that, in future CoIS, design objectives may not be so tightly controlled, but rather serve increasingly as an overall common direction to develop an application with a greater involvement of a large number of actors. This implies a multitude of stakeholder perspectives having influence over the design objectives and that these perspectives may be dynamic over time. In addition, a higher purpose that reflects societal benefits rather than primarily engineering-dominating objectives may be increasingly guiding the emergence of the specific design objectives. In the arena focused on public safety, this is reflected in the SSRS mission to save lives at sea. Such a higher purpose mission might unite an entire community of actors representing the system and can direct them toward a common objective. Compared to traditional CoPS system integrators that usually safeguard the system boundaries, and thereby control and sometimes restrict the introduction of additional system functionality [54], a new landscape seems to emerge where a wider range of systems that have the potential to contribute to the overall design objectives can be integrated, based on mutual agreement and their potential to contribute to the overall mission. This alters the focus of the design objectives to be more open as well as representing an increased level of generativity.

Second, the boundaries of complex systems have traditionally been associated with the authority to allocate resources, determine incentives, and team interdependencies in general [23], [55]. Usually, system integrating firms are largely in the lead of these activities, although a network of suppliers may be involved [21]. In contrast to this, the findings show that CoIS have increasingly fluid boundaries regarding to what the systems is and who is involved. The overall system is rather defined by the mission or task at hand and there may be no one single entity or group having control over the system. This alters potentially the role of a system integrator, as described in CoPS literature [21], [32], [56], [57]. The findings indicate that, in CoIS, decisions regarding what is part, or not part, of the system depend on the specific configuration, data dependence, use case, and is ultimately emerging through recombination. The common goal becomes more prevalent in driving the actors to form a collaborative environment, in which multiple stakeholders can work together to provide the integrated system or SoS solutions that also serve the individual actors. In WARA-PS, this changed logic in relation to system boundaries is prevalent in the initial design of the system, where it was chosen to create a system without a rigid boundary that allowed generative approaches. This includes data gathering and sharing, i.e., data that are freely shared across organizational boundaries, among the stakeholders involved.

Third, traditionally, architectures in complex systems have been conceived as means to achieve the desired system characteristics and are central for addressing a growing complexity [21], [44], [56], [58]. In relation to this, it has been stressed that system integrators need to have dynamic capabilities allowing them to envisage and produce new product architectures [21]. The findings in this article indicate that such architectures are undergoing several changes that may create a necessity for system integrators to develop additional complementary capabilities, not least due to an increased dependence on internal and external data. A new type of architecture, building on a platform-based partitioned layered logic [cf. 11], enables different configurations and representations across levels, by integrating core and peripheral parts, platforms and applications, and hardware- and software-based resources, across time. It may be that the capability to master a combination of architectural and modeling approaches, in combination with additional organizational procedures, will facilitate future engineering work of CoIS [8]. The existing literature on complex systems has emphasized the context of multiple stakeholders and their objectives as an important factor influencing system engineering and management [59]. Such a context has been described from a rather strictly controlled supply chain perspective [44]. The observations from WARA-PS show a more loosely coupled network with complex interrelations, operating as a complex innovation ecosystem around the research arena. Criticality is addressed in each of the subsystems that can be tested independently before integration into the larger system, the C2 system, and additional procedures enabling safe demonstrations. These are applied as an integrated system approach to achieve system safety [60]. The system allows generativity in terms of new, extendable, and reconfigurable functionality, novel contributions, experimental configurations, and increasing generative relationships. This indicates the use of an evolving and differentiated strategy to enable the combination of criticality and generativity.

Fourth, predictability and emergence are quite pronounced in the case of WARA-PS. It seems that a new focus is emerging beyond system failures and criticality. In the context of complex systems, the knowledge required for innovation may emerge in an unpredictable and prolonged manner. This may have several implications for CoPS management and the role of system integrators. CoPS management needs to increasingly be built on several critical capabilities, i.e., capabilities for absorptive capacity to identify and evaluate opportunities emerging from advances in science and technology; integrative capabilities to be able to integrate internal and external components/subsystems into existing architectures; coordinative capabilities to coordinate the long-term direction of the development of emerging bodies of knowledge or technologies; and generative capabilities to be able to innovate at both component and architecture level, independent of external sources. Traditionally, system integrators are particularly strong in integrative capabilities and are required to have a larger amount of knowledge beyond what they currently do [57], [61], [62], [63]. To keep up with current developments, system integrators possibly need to strengthen their capabilities related to the other three areas. However, it may of course be questioned to what extent all these capabilities need to reside at traditional system integrators or if new actors will emerge that take over part of these roles. This remains to be seen.

In addition, in CoIS, rather than a focus on predictability in the system, the focus is on creating prerequisites for generativity while being able to maintain criticality without relying strongly on predictability. This implies that the overall knowledge base is not residing predominantly at one dominant or small group of actors, but rather spread out among the contributing actors. This seems to be more based on flexibility and overall concertation, as demonstrated in the case by replanning, reconfiguration, supporting procedures, and data-driven approaches that are used to identify and respond to unexpected events based on overall situation awareness. As such, this represents a different perspective on not only predictability and emergence but also on the resilience in relation to robustness and criticality in CoIS [64].

Last but not the least, the fifth aspect, learning and adaptability, has been linked to system changes across product generations

[59]. This may affect system integration and the surrounding network of actors. Typically, in traditional CoPS industries, the system integrator has a large say in who to collaborate with, what to make in-house, and what tasks to outsource [21]. In relation to this, a system integrator needs to have knowledge that goes beyond what they need for the systems they integrate, including a broader understanding of the knowledge landscape in their industry [32], [57]. The findings indicate that not only learning and adaptation are more emphasized in CoIS, but also that system integrators may be less in control over the learning and adaption process. Especially when constituent systems as parts of a larger system are considered in an SoS setting, decision-making may be more decentralized, with each actor taking responsibility for their respective system and having the necessary knowledge for operating their part of system. In such a setting, overall system integrators may need to develop additional knowledge and approaches that go beyond each of the system, providing the "glue," also in terms of criticality, for the overall system.

Learning and adaption in a CoIS context implies that systems may be under continuous development to be adaptable and display a high degree of dynamics with a core system with possible expansion of the constituting parts of the system as well as reconfigurations of the architecture. This may be further supported by additional continuous development of enabling conditions that create dynamics. As reflected in the findings, such enabling conditions are created in the system architecture, e.g., through generative APIs, but are also related to the increasing role of AI solutions and their inherent dependence on data. As illustrated in the findings, but also reflected in contemporary literature [see e.g., 11], such approaches may strengthen system criticality while at the same time enabling further generativity. However, this poses also additional complexity challenges due to a decreasing degree of predictability as well as increasingly fluid boundaries of the system. The findings also indicate that such learning and adaptation may center around a mission reflecting a higher purpose, e.g., related to the ultimate societal benefits as engineering management increasingly needs to consider a broader perspective of the system and its function in societal development.

As a representation of a CoIS, the findings in relation to the research arena WARA-PS highlight various potentially important insights on the future engineering management characteristics of CoIS having implications for CoPS management (see Table I).

TABLE I
ASPECTS OF CoIS

Aspects of complex systems	New characteristics of CoIS
Nature of the design objectives	• Generative, leaving potential for future development • Reflecting higher purpose and societal benefits • Changing over time and crossing domains
Nature of design boundaries	• Different levels with multiple foci • Fluid and diffuse and constantly evolving • Multitude of stakeholders shape and redirect the system dynamics • Unbounded data sharing
System architecture	• Reconfigurable architectures • Combinations of different modeling approaches • Increasing role of data • Evolving and differentiated strategy to enable the combination of criticality and generativity (e.g. generative API:s)
Predictability and emergence	• Approaches allowing emergence • Replanning, reconfiguring, and supporting procedures • Data as part of achieving criticality
Learning and adaptation	• Core system enabling learning and adaptation • Expansion and scalability as part of the design objectives • Adaptations through reconfigurations of the architecture • Continuous development of enabling conditions • Higher purpose mission facilitating learning

B. Accentuated Tension Between Criticality and Generativity in CoPS Management

Overall, the findings show an accentuated tension between criticality and generativity driven by increasing demands on the systems through more generative design objectives reflecting a higher ambition for societal benefits. The case indicates that a feasible response is an SoS approach benefitting from AI using a wide set of data where learning and adaptation are becoming an increasingly central aspect throughout the system's life cycle. This results in a potentially exponential growth of emergent behaviors both during development and operation, which challenges current approaches of predictability (and traceability) in critical systems development. Further, such a new landscape for CoIS calls for novel approaches to combine criticality and generativity, not least as generative technologies potentially play an important role both in mastering the increasingly fluid boundaries and to increase the system ability to handle criticality. While one important such approach could be layered partitioned architectures [11], this article also shows the importance of allocating safety at right levels in the system to enable the combination of technical solutions and operational routines to handle the fluid boundaries. Bearing in mind Perrow's dystopia in NAT [22] that basically was grounded in difficult to understand emergent behaviors during operation of a complex system, our findings suggest that we should strive for fluid boundaries and generativity within certain bounds. The ability to expand these bounds calls for novel approaches both for criticality and generativity leading to systems that could be referred to as "bounded generative and increasingly so in an SoS approach. An important goal for development of future CoIS then becomes successively expanding the bounds of generativity while fulfilling the system's criticality function.

The overall findings thus reflect a new understanding of the prerequisites for CoPS management, partly alternating and partly complementing current CoPS management approaches building on a movement toward enabling the inherent generative characteristic of CoIS increasingly becoming SoS [36], [37], [38], with the challenging task of not losing sight of system criticality [16], [17]. This is visualized in Fig. 4.

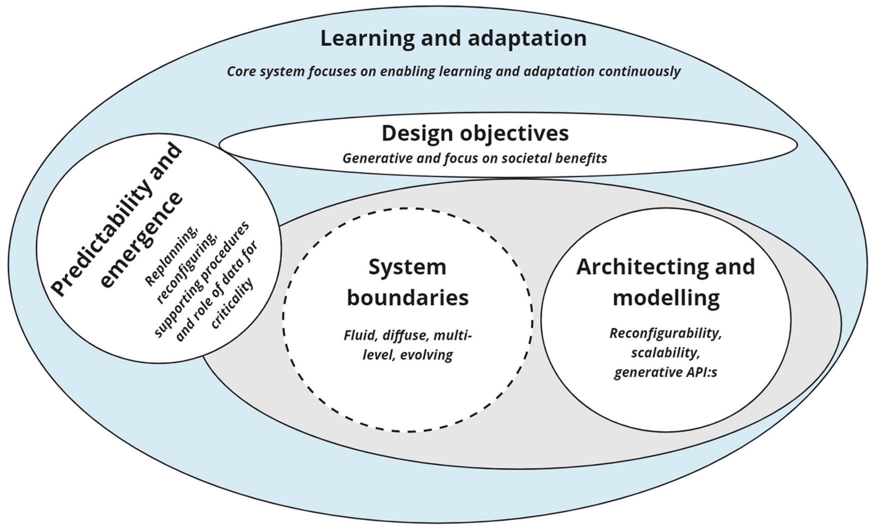

Fig. 4. Changes in the five aspects and their emergent engineering management logic in CoIS.

C. From CoPS to CoIS Management

In the transition from CoPS to CoIS, the role of the system integrator as reflected in traditional CoPS literature [21], with its focus on control and criticality still seems to be relevant, not the least with the continued importance of criticality. However, as it appears, a system integrator, as one single firm, could become less dominating in an SoS context with a diversity of actors representing constituent systems that all fulfill criticality in their independent systems. Rather, as the findings indicate traditional system integrators in CoPS contexts need to be able to expand their contributions beyond those normally addressed by CoPS system integrators, i.e., by developing capabilities and approaches that support the constituent systems to work together in a less controlled and more dynamic context.

More specifically, as a first implication, fluid boundaries and SoS approaches imply the need for novel management approaches. These do not necessarily need to reside at the traditional system integrator. Also, these approaches need to be applicable in contexts where there is substantially less control than in traditional CoPS with rather well-defined roles and actors [e.g., 21]. This includes approaches that support the inclusion, exclusion, and recombination of constituent systems in an SoS to respond to the evolving usage needs over time. These management approaches may help define, expand, and manage the bounds of generativity for an SoS.

Second, the emphasis on negotiation of design objectives alters the role of traditional system integrators somewhat. Rather than being in control of the involvement of actors and decisions, system integrators may need to face situations where the design objectives are negotiated without a dominating involvement of an overall system integrator. Also, a system integrator on the constituent system level may not have much influence over the design objectives of the overall system. Therefore, the system integrator of a constituent system may be forced to define the bounds of generativity for its constituent system without being the integrator at SoS level. To some extent, this is also reflected in traditional CoPS literature that acknowledge subsystem suppliers as large firms that may act as system integrators in other projects [21]. However, in contrast to this literature that frames the system integrator's task as drawing up the overall specifications mapping the performance of each subsystem and the interactions between subsystems, in the new setting of CoIS, the task division between SoS system integrators and constituent system integrators is changing. Rather than a focus on control over the system, CoIS actors could be guided by an awareness of the situation, i.e., what needs to be addressed with the system. This reflects a capability to navigate and rely on a looser control, such as allowing constituent system's actors initiatives or consensus/negotiations to combine different development logics on a SoS level in an evolutionary way to achieve an expanding bounded generativity, combining generativity, and criticality in a more fluid ecosystem.

Third, much of the existing CoPS management practices seem to be relevant from a constituent system integrators perspective in the setting of CoIS. For instance, it appears that the criticality needs in relation to each of the constituent systems could be addressed in line with current practices. However, it seems that addressing criticality at an SoS level would require additional and novel approaches that also appear as important for managing the bounds of generativity for the SoS.

Fourth, as part of novel approaches for CoIS, there may be a need for core systems functioning as a platform supporting the SoS management. This is likely facilitated by further evolving architectures that enable generative approaches and the management of bounded generativity [11]. In such architecture, core systems may function as a platform for the overall SoS. Such core systems resemble CoPS in the sense of complexity and the need for criticality management but appear to differ in the sense that they could be seen more as a service for the overall SoS. Compared to traditional CoPS integrators that tend to move downstream to provide services to maintain their products [21], CoPS integrators may be offering a new type of service as a platform in an SoS context. Although this may be a new opportunity for system integrators, it also reflects a new situation with potentially reduced control and likely strong demands for facilitating the expansion of the bounds of generativity in many aspects.

Fifth, the introduction of AI and intelligent functions in CoPS are expected to appear on several levels. Current applications are still dominantly isolated in single functions or tasks within a subsystem. The inclusion of such functions appears to fit with the CoPS paradigm, as a complex multitechnology system [9]. In a way, AI could then be seen as just one more technology being used in a CoPS system. However, much of the benefits from AI are expected to appear in a more integrated level of systems and in SoS contexts, implying the need for management of more loosely coupled and generative functionalities that are recombined on abstract levels. Such an inclusion of AI goes beyond what traditional CoPS firms are capable of and may require new approaches.

VI. Conclusion

As AI is increasingly expected to become an integrated part of complex systems, increasingly being realized as SoS, the implications of AI for engineering management cannot be considered outside of the complex context it will be part of. With the purpose of exploring the implications of AI in a complex context of emerging CoIS, especially in relation to two seemingly contradictory but combined properties, i.e., generativity and criticality [11], this article builds on findings from an SoS research demonstration arena on public safety.

Several contributions can be outlined. First, this article shows that novel and extended approaches to combine criticality and generativity in engineering management are important to be able to benefit from the generative character of AI, and its potential contribution at several system levels. Second, we suggest a new underlying logic for engineering management, based on what we propose as "bounded generativity," to manage increased generativity on different levels while still fulfilling criticality needs. Such bounded generativity could, for instance, be supported by platform architectures that make it possible for actors to strive for both controlling the bounds of generativity and expanding these bounds when additional generative opportunities emerge. Third, such bounded generativity can materialize at different system levels, i.e., at a constituent system level to express the bounds of these systems' application for maintaining criticality of the constituent systems as well as at an SoS level to negotiate possible generativity in the use of constituent systems being combined and recombined at SoS level and offering an overall bounded generativity.

The transition of CoPS into CoIS and the consequences for engineering management are outlined based on an exploration in relation to five aspects of engineering management [23] that point at the implications for contemporary CoPS management. Overall, the article shows that, while CoPS management practices are still relevant for some types of constituent systems, the emergence of CoIS, with its specific engineering management characteristics, potentially requires additional management capabilities that go beyond the current role of traditional CoPS system integrator firms. Such additional management capabilities need to address AI in an SoS context, as many of the benefits of AI are expected to materialize in an environment that builds on a more dynamic interaction both between constituent systems and with the wider context. Five potentially important extensions of CoPS management emerging into CoIS management include a wider negotiation of design objectives including more actors, more fluid system boundaries, management of bounded generativity to support the coexistence of criticality and generativity, providing platform integration as a service to support bounded generativity at SoS level, and finally the inclusion of AI at levels beyond isolated functions in subsystems. This reflects a new landscape for the CoPS industry, where traditional CoPS system integrators of constituent systems are expected to play a less central role.

Although our research approach has several merits, also some limitations can be identified. The research approach allowed us to study a representation of a phenomenon before its actual full realization [3]. It has thus allowed us to capture several of the implications we expect to come along with the emergence of CoIS. This fulfills our research purpose to explore future engineering management implications. However, such an approach may not fully reflect the way CoIS materialize and further articles are necessary to follow the emergence of CoIS, its peculiarities, as well as emerging practices.

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Youshan Yu received the master's degree in mechanical engineering from The Hong Kong University of Science and Technology, Hong Kong, in 2009, and the master's degree in aerospace project management from the L'ISAE-SUPAERO, Toulouse, France, in 2016. She is currently toward the Ph.D. degree in industrial engineering and management with a specialization in industrial management with the Department of Management and Engineering, Linköping University, Linköping, Sweden.

She has previously worked as a Project and Systems Engineer in various fields, such as aeroengine cleaning, pharmaceutical automation, and subsea oil and gas development. Her research interests include future management of emerging complex intelligent systems, with a focus on the coexistence of generativity and criticality.

Nicolette Lakemond received the Ph.D. degree in industrial management from the Linköping University, Linköping, Sweden, in 2001.

She is currently a Professor of industrial management with the Department of Management and Engineering, Linköping University, Linköping, Sweden. She has previously performed research on innovation in complex and interorganizational settings, including buyer–supplier collaboration and customer's role in the knowledge supply chain of innovation, interfirm collaboration in digitalization projects, and knowledge integration in open innovation. Her research interests include management challenges related to the emergence of complex intelligent products and systems.

Dr. Lakemond is a member of the Academy of Management and the Continuous Innovation Network.

Gunnar Holmberg received the Ph.D. degree in machine design from the Linköping University, Linköping, Sweden, in 2003.

He is currently a Director of Business Development, SAAB Aeronautics, Linköping, Sweden, and an Adjunct Professor with the Collaborative Product Development, Department of Management and Engineering, Linköping University, Linköping, Sweden. He has previously performed research on product development for complex systems with long life cycles, and he has held various management positions at SAAB over the years, including forming and leading international R&D collaborations. His research interests include management challenges related to the emergence of complex intelligent products and systems.

Dr. Holmberg is a Member of the Royal Swedish Academy of Engineering Sciences and Member of the executive committee for ICAS, the International Council for Aeronautical Sciences.