Digital Transformation in Complex Systems

Nicolette Lakemond, Gunnar Holmberg, and Anders Pettersson

Abstract—Complex systems increasingly include embedded digital technologies that interact with and are constrained by physical components and systems. Although these systems play a central role in our society, they have only been scarcely addressed in contemporary research on digital transformation and the organization of innovation. This article explores the digital transformation in complex products and systems and its consequences for organizational design. A longitudinal study of avionics development since the 1950s uncovers the application of digital technologies, first as a sequence of initial experiments, followed by the use as add-on functionality, then as an integral part of achieving critical functionality in systems, and currently combining add-on and critical functionalities enabling generativity. The findings emphasize the evolution of the intricate relationships between the systems architecture and organizational approaches when digital technology enables and enforces increased complexity, expanded functionality, increased systems integration, and continuous development. These nested dependencies are accentuated by the complexity that has emerged beyond human cognition, where increasingly sophisticated boundary objects based on modeling, simulation, and data play an important role in the organization’s ability. Boundary objects relate and decouple the multifaceted dynamic relation between organization and architecture. The results also extend existing perspectives on platform strategies by outlining the importance of generativity in combination with criticality control, rather than market control. Criticality control in combination with generativity has become imperative not least as generative digital technologies have become central in achieving critical properties such as safety. Several avenues for further research are outlined.

Index Terms—Complex product systems, digital transformation, management of innovation, organization design, product design, systems engineering, technology-based organizations.

I. INTRODUCTION

During the last decades, many complex products and systems (CoPS) have transformed from mainly physical-based product compositions, recognized by having mass and shape, into more software-defined hybrid digital and physical compositions [1], [2]. This has resulted in less predictable engineering tasks and an increasing degree of uncertainty and learning involved [3]. As embedded software has become an important part of CoPS products, CoPS firms have gained extensive experience in integrating physical and digital aspects [4], [5], [6]. Despite this extensive experience, and particularly in the face of the increasing body of literature on digital innovation, empirical research addressing the digital transformation in CoPS is still scarce.

CoPS are defined as “high cost, engineering and software-intensive goods, systems, networks, infrastructure and engineering constructs and services, many of which are vital for industrial growth and the modern economy” [2, p. 6–7]. Examples of CoPS can be found related to many of the infrastructures that are critical for society and include transportation (cars, traffic systems, aircraft), energy supply (power plants, electricity grids), and ICT (internet, mobile communication). CoPS-based firms have long-faced challenges related to complexity and the simultaneous consideration of properties such as safety, security, reliability, and cost [7], [8], [9], [10], [11]. Due to its complexity, CoPS innovation has been found distinctly different than innovation for other type of products [7]. In CoPS literature, the term “complex” is used to denote the customized nature, degree of new knowledge involved, breadth of knowledge, and more recently the emergent and integral nature of the CoPS innovation context [1], [12]. In addition, aspects such as systems integration [4], product architecture and modularity [9], [10], [13], [14], and management of the (inter-)organizational context [12], [15], [16], [17] are central.

Largely outside the context of CoPS, an extensive body of research related to digital transformation is emerging and changing perspectives on management [18]. Digital transformation has been defined as “a process that aims to improve an entity by triggering significant changes to its properties through combinations of information, computing, communication, and connectivity technologies” [19, p. 118]. The focus on digital innovation has given rise to almost unprecedented expectations on new types of business models and innovation and a notion of different emerging types of architectures and technology platforms, new organizational approaches, and ecosystems [20], [21], [22], [23], [24], and [25]. Insights into digital transformation and innovation are often originating from social media, mobile, analytics, or smart embedded devices, and a fascination with the business models of companies such as Uber and AirBnB. The technologies and infrastructures behind, as delivered by CoPS industries, have received much less attention. It has been argued that CoPS industries need to transform their innovation strategies analogically to other types of industries [26], [27], while the peculiar aspects of CoPS, their implications, and the already considerable experience of CoPS with digital innovation driven by advancements in communication, sensors, control systems, and processing capability have been rather ignored.

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Building on the inherently different characteristics of CoPS industries, this article sets out to contribute with a further understanding of digital transformation and innovation in the context of CoPS. Based on our research question how CoPS firms navigate their approaches toward integrating digital technologies over time, the purpose of this article is to explore digital transformation and innovation and the associated CoPS aspects. The aim of the article is to build an understanding of digital transformation in CoPS and connected future management capabilities that contribute to the organizational needs of CoPS firms.

The findings are based on a longitudinal study of avionics development in the aviation industry. This industry represents a system-building industry with long-lived, extremely complex high-technology products, with strict safety, security, and reliability demands. It shares similar characteristics with many other CoPS system-building industries and critical infrastructure in society, including transport, healthcare, finance, and energy. The aviation industry offers unique insights as it has been one of the pioneering adopters of computing [28], sophisticated control systems [29], sensing technologies integrated with physical systems [30], and health monitoring [6].

By exploring these past and current pioneering practices, this article contributes to a rich understanding of digital innovation in CoPS, its emergence over time, the organizational approaches associated, and discusses implications and further research avenues.

II. THEORETICAL BACKGROUND

A. Central Innovation Aspects in Complex Systems

CoPS contexts are characterized by distinct challenges related to complexity, systems integration, systems architecture, and (inter)organizational design [4], [9], [10], [11]. Complexity is related to the high number of customized components, the breadth of the knowledge and skills required, and the extent of new knowledge involved in development and production [1]. More recently, the CoPS innovation context has been described as emergent and situated [12], something which emphasizes the need to complement control as a strategy to deal with complexity with the ability to maneuver [31]. All these facets result in complex interactions between operational needs, capabilities, business processes, and organizations involved.

Systems integration is a crucial capability as CoPS companies face huge challenges related to complexity. One of the main tasks of CoPS industries is to define and combine all the necessary inputs for a system and to agree on a system’s future development path [4]. This capability has evolved as an engineering practice in the wider discipline of systems engineering but is also considered a strategic organizational activity in CoPS industries. From this perspective, it concerns “the way in which firms and other agents bring together high-technology components, subsystems, software, skills, knowledge, engineers, managers, and technicians to produce a product in competition with other suppliers. The more complex, high technology, and high cost of the product, the more significant systems integration becomes to the productive activity of the firm” [4, p. 1110]. One key challenge in systems integration is selecting and orchestrating the system content so that value is achieved beyond the sum of its components [32].

The complexity of a system is reflected in its architecture, referring to the structure and relationships within a complex system and often expressed in terms of layers ranging from technical infrastructure to system operations [33]. A well-chosen systems architecture may enable new levels of integration and allow for new functionality [14]. This requires deep architectural knowledge that needs to be maintained over time [21] and generated together with component knowledge [34], [35]. The relevant system integration, architecture, and component- and subsystem-level knowledge are also important for moving from one product generation to another [16].

Over time, the perspectives on modular versus integrated product architectures may change considerably [36] resulting in transitions of the system architecture. Along with architectural transformations, CoPS innovations progressively increase architectural complexity as new subsystems or increasing functionality is added [37].

CoPS systems are usually developed and produced in project-based organizations that incorporate a multitude of stakeholders [2], [38]. In some CoPS, such as in aviation and military systems, governments, standards bodies, and regulatory bodies are important stakeholders and influence innovation processes related to safety issues and interfacing standards [37]. Projects have been described as a suitable form to coordinate the internal and external activities for developing and producing CoPS and support performance tradeoffs and the collaborations in a network of suppliers, users, government agencies, regulators, production partners, and sometimes competitors as firms work together in projects while competing in markets [7] [10], [39]. A project-based organization facilitates the management of unforeseen and unforeseeable features that may occur [7] and allows for flexibility [38]. Development standards and model-based systems engineering (MBSE) are often used to complement organizational approaches [40], [41]. An important rationale for using modeling and simulation is their potential to reflect multifaceted perspectives and interests [33]. Through transparency and actionability, simulation models can create new information about complex systems and help engineers and managers make complex design choices [42]. In the context of flight simulators which are software-based, Davies and Hobday [2] have pointed at the limits of rational formalized approaches and argued for the use of complementing approaches such as informal meetings and integrated project teams, something that has also been addressed with human-centered adaptive and agile methods [43], [44]. CoPS organizational design, thus, seems to rely on a combination of intra- and inter-organizational approaches as well as formal and people-based activities.

The CoPS innovation context can be summarized in relation to the aspects described above reflecting its specific nature and conditions, including complexity, systems integration, systems architecture, (inter-)organizational design (see Table I).

B. CoPS and Digitalization

The rise of digital technologies has opened up a new innovation landscape, including different architectures, technology platforms, and organizational approaches crossing traditional industry boundaries, increasingly relying on industrial
platforms and ecosystems [20], [21], [22]. Established industrial firms are transforming their innovation strategies and processes to embrace digital innovation [26], [27]. However, studies often consider digitalization in isolation and outside the context of the (physical) system in which digital technologies are implemented. For instance, Svahn et al. [27] base their findings on a study of digital innovation in the automotive industry but their empirical focus is delimited to Volvo Cars’ connected car initiative. The connected car initiative provides complementary functionality, such as in-car entertainment, audio system, voice control, and smartphone interoperability. It can be considered as an interesting example of add-on digital innovation rather than integrated and more critical software-based functionality, such as emerging driver-assist technology.

While the literature on digital innovation is evolving based on empirical studies that consider the digital innovation relatively isolated from its wider systems context, the existing CoPS literature has since long recognized the centrality of the system context and embeddedness of software. More than 20 years ago and referring to the 1980s, Hobday and Brady [3, p. 4] noted that “Over the past two decades or so, the diffusion of software engineering into the design, development and manufacture of CoPS has assumed ever-increasing importance. Embedded software has improved the control, flexibility, and performance of many products, while systems integration and software engineering have become central to the mechanisms of innovation in many CoPS. The growth of embedded software has transformed the nature of systems, projects, and processes of innovation. Software has also enabled concurrent engineering, the parallel design and manufacture of major system components using predicted data and complex models.” Since then, the role of software has increased rapidly and changed the landscape of CoPS development.

One central theme in the literature on digitalization has been related to generativity. This has been described as a system’s ability to create, generate, or produce a new output, structure, or behavior without any input from the system’s originator [45]. Nambisan et al. [46, p. 3] define generativity as the “capacity exhibited by digital technologies to produce unprompted change (through ‘blending’ or recombination) by large, varied, unrelated, unaccredited and uncoordinated entities/actors.” It has been suggested that generativity provides a measure of a system’s capacity to foster innovation [47] and enlarges the possible innovation space by including external actors outside the full control of a system’s owner. CoPS systems may, similar to digital systems that have been previously explored, also emerge beyond the original design intent.

The extant literature on generativity has focused on different aspects and/or consequences of generativity. One perspective is the focus on how different types of system architectures promote and facilitate generativity in digital systems. Layered system architectures and platforms [20] are considered to promote generativity and provide open interfaces for other organizations to contribute to the system. These types of system architectures are connected to platform-based approaches to do business amid a large network of actors in an organizational ecosystem [46], [48] stressing a possibility to achieve market control through standardization [49].

Compared to many of the platform-based systems that have been studied, CoPS-specific properties related to system criticality, e.g., safety, security, reliability, provide different prerequisites. CoPS industries have an extensive responsibility and are required to have a certain degree of control over their products and processes, e.g., through formalized systematic controls and management tools for controlling processes [2]. Digital technologies, on the one hand, enhance the systems possibilities to emerge beyond what was imagined when they were designed, but, on the other hand, infuse an increasing challenge for CoPS firms to safeguard the system’s critical functions. This challenge is distinctly different than achieving market control. To our knowledge, this has hardly been discussed in the current literature.

**III. RESEARCH DESIGN AND METHOD**

To generate an understanding of digital transformation in CoPS and its specific innovation and organizational aspects, this article builds on an in-depth narrative account of avionics evolution at Saab AB, a Swedish company in the aviation and
defense industry. Saab was founded in 1937 as an early consolidation of the Swedish aircraft industry and has a long tradition of developing and manufacturing aircraft, complementary products as well as other defense products. The goal of this case study is to generate an in-depth conceptual understanding of digital transformation in CoPS that at least partially can be transferred to other CoPS settings.

CoPS firms in the aviation industry feature long-lived products, relying heavily on properties such as safety, security, and reliability, and have a long history of increasingly embedding digital technologies into products. Avionics have grown in importance in recent decades, representing a large part of an aircraft’s value and functionality achieved through digital technologies. These digital technologies often interact with and are constrained by physical behaviors, components, and systems, in particular, control systems that place strict requirements on safety, security, reliability, and real-time performance [50]. The specific characteristics of avionics are considered relevant and paramount not only in aviation but in a wide range of industrial domains, including emerging domains such as unmanned systems [51]. Therefore, there are ample opportunities for transferring the study results beyond the specific case of avionics (cf. [52]).

The research approach is a process study [53] that captures digital innovation and transformation together with organizational adaptations and by taking time into account. To capture the complexities involved, we designed our research and organized data gathering by creating interaction between researchers and practitioners to combine and capture different perspectives, knowledge, and backgrounds, as recommended by Gioia et al. [54]. Although the study is a retrospective account of events and their interrelationship, the data collection was inherently characterized by “withness” [55], i.e., involving those that have lived the experience in the company in the research process. Two of the co-authors of this article have extensive (>30 years each) experience in different roles at Saab. One is employed part-time as an academic researcher. The other has had key roles such as Chief System Architect, and Head of Avionics Development during the Gripen development. Their experiences have been complemented with interviews with current and retired key individuals at Saab.

To mitigate potential bias further, we have used numerous company internal and publicly available documents describing events in Saab’s history and corroborating the emerging narrative. The extensive secondary information includes large amounts of historical documents and publications. These experiences are systematically documented in a book series called the “Saab memories.” The Saab memories have been produced annually since 1988, in books published by the association Saab Veterans Club under the auspices of an editorial board. The memories capture experiences dating back to Saab’s early history, including extensive material on the avionics development over the years, written by the now-retired key individuals involved. They can be considered as narratives to create situated understandings of experiences to build an organizational memory and create meaning (cf. [67]).

Additional historical material is available via the website of another association, Friends of DataSAAB, which until 2017 actively aimed to promote education and historical research for the public good within computer technology from the 1950s onwards, focusing on the Linköping region (Sweden), and the former DataSAAB company.

To reflect the wider industry perspective, we have gathered additional secondary material such as conference publications at two major aviation conferences, organized by two industry-related associations ICAS and AIAA. A visit to the Musée de l’Air et de l’Espace at Le Bourget in France, provided us with an additional external reference to compare the timing of early aviation digitalization by comparing aircraft prototypes and study the development of the legendary supersonic passenger aircraft Concorde.

Table II provides an overview of the main data sources categorized by the type of data.

The analysis of the abundant empirical material builds on numerous hours (>100) of discussions and reflections on avionics system development in relation to the main overarching concepts of CoPS and digitalization in the literature. We have applied a temporal bracketing strategy to capture ambiguity, nuance, and transition points in the temporal evolution (cf. [53]) of avionics. The analysis process can be described as an abductive approach [67], building on dialogical interaction around an emerging narrative with an expanding dialogical community [55] and focusing on mitigating the risk for bias. While initial sensemaking activities took place in the small group of authors, the emerging narrative was triangulated through further interactions and discussions with a broader group of key individuals at Saab. In addition, the narrative was corroborated by expanding the dialogical community into the broader aviation industry. Among others, we have presented our (intermediate) findings to practitioners and researchers with a deep insight into the field, including at the 2018 ICAS aeronautical sciences conference.

IV. AVIONICS AT SAAB

The aviation industry has experienced rapid technology development in avionic systems for several decades. Saab has been developing and producing aircraft since the 1930s, both military and civilian. The industrial development projects for developing the Draken, Viggen, and Gripen aircraft have been among Sweden’s largest in their respective eras. The development of these aircraft was accompanied by an extensive demand for new knowledge creation and has resulted in new applications in several areas. We have studied the architectural evolution and organizational adaptations made by Saab to integrate digital technologies, towards avionics that now rely largely on software-based functionality. As the empirical narrative shows, digitalization at Saab can be traced back to the 1950s with direct connections to the development of the information systems research field [68] and with Saab as one of the pioneer suppliers of the first large computers [59], [60] as a side product of its aircraft development. With avionics in focus, our study spans organizational and technological development over time, including technology advancements in the different aircraft designs and the associated design and engineering practices. It provides an overview covering more than 60 years and the transition toward digitalization in the products, the engineering design tools, and the corresponding organization (see also for a summary Table III).
TABLE II
DATA SOURCES

| SOURCE                          | FOCUS AND DESCRIPTION                                                                 |
|--------------------------------|---------------------------------------------------------------------------------------|
| Interviews                     | Capturing past but mainly present and current avionics architecture:                  |
|                                | - Five interviews with key individuals with roles as Chief Architect, Head of Avionics in the development of Gripen, Systems architects, former CTO and Head of Operations |
| Process as withness            | Observations and experiences over time on avionics development:                       |
|                                | - Direct and documented memories from the two co-authors from within the organization with more than 30 years’ experience each in different roles at Saab. |
|                                | Reflections on past interpretations in the light of the present:                     |
|                                | - During 2018-2020 more than 25 informal discussions by co-authors with their colleagues within the organization and their network, including current and former CTO, system engineers, system architects, software engineers, business developers. |
|                                | Feedback on earlier drafts on case description as part of validation:                |
|                                | - Comments from: Vice President Corporate Strategy and former Head of Development for future products; Head of Future Combat Air Systems and Former Head of Development Gripen; Director of Operations Development - now retired; Former Head of Strategy Aeronautics, now Head of New Programmes |
| Archival documents             | Capturing and triangulating understanding of internal developments at Saab in documented organizational memories: |
|                                | - Saab memories and Saab veteran club (www.saabveteran.se) and documents available through the association - Friends of DataSAAB (www.datasaab.se) including key publications [56] [57] [58]: |
|                                | Evidence and triangulation on developments at Saab through publications and presentations: |
|                                | - Papers published at international conferences and books including [59] [60] [61] [62] [63] [64] [65] |
|                                | Capturing wider aviation industry developments:                                      |
|                                | - Documentation from regular conferences (ICAS and AIAA) in the aviation industry. |
|                                | www.icas.org, www.aiaa.org                                                          |
|                                | Capturing industry standards:                                                       |
|                                | - ARINC standards - www.aviation-ia.com/activities/aecc                             |
|                                | - DO-178B/C – available through www.rtca.org and [66]                                |

A. Early Digitalization and Avionics at Saab

From the 1950s and onward, digitalization started to play a role at Saab. In 1949, one of the pioneers at Saab, Börje Langefors, was recruited to work with analog devices for stress calculations. Langefors started to look for expansions into digital computations. He explored the possibilities in Sweden with its first electronic computer, called BESK, and investigated the developments in the US including a study trip in 1954. This early period of digitalization at Saab represents developments to support engineering tasks with digital calculations, e.g., shape continuity, aerodynamics, and stress, as well as the first steps toward a digital navigation computer in the aircraft. The organization of Saab was at the time dominated by functional perspectives which were represented in a traditional hierarchical line organization. A few key individuals in managerial positions had great influence over aircraft and avionics development. The development of aircraft was based on in-depth knowledge of the different areas represented in the different departments. Initially, digitalization initiatives related to stress calculations were realized in a department serving other technical departments. Also, initial developments toward the airborne computer for the Viggen were carried out in the separate newly created technical department DataSAAB.

B. Airborne Central Computer in Viggen and Founding Principles for Avionics

In the early 1960s, most senior managers at Saab still considered the first developments toward digitalization as a subordinate issue in aircraft design and production. A couple of leading individuals in the systems department at Saab supported the idea of a strong electronics system, and if possible, with a computer function. The central computer’s functional safety was discussed. The system was classified as not safety critical, as “non vital apparatus from an aviation safety point of view” [60] meaning that the plane could fly home even if the computer stopped working. By the end of the 1960s, several avionics principles had been identified by Sjöberg and Folkesson [62]. Since then, these principles have been important for the development of avionics. They recommend the use of a central computer for information sharing but also point at the importance of distinguishing between safety critical and noncritical systems. At the time, the latter built on the belief that flight safety could not rely on computers. The Viggen performed its first flight in 1967 with a centralized general-purpose computer contributing to several functions such as navigation and landing.

During the 1980s, technology development for an electronic flight control system was achieved in the Viggen program through a demonstrator. The demonstrator system was a single
channel system with mechanical backup, combined with loading of the aircraft that made it unstable. Its purpose was to demonstrate and evaluate solutions to control an unstable aircraft with computers. This paved the way for the future implementation of computer systems for flight-critical applications and fly-by-wire aircraft, i.e., using digital technologies beyond add-on functionality.

### C. Gripen System – Gripen A/B, Increased Complexity, Flight Critical Computer Systems, and New Organizational Approaches

The Gripen system was developed as a successor to Viggen and performed its first test flight at the end of 1988. It incorporated technology advances; engines had become more efficient, electrical flight control systems could now completely replace mechanical, and new composite materials were developed. Software played an increasingly important role in the development and the product. It included integrated instrument presentations on larger screens in the cockpit, so-called glass cockpits, enabling functional flexibility for the future.

With the technology advancements, the complexity of the aircraft had reached a level such that Saab increasingly relied on complementary actors in a global supply chain and used several external system solutions both for technology access and for cost reasons.

From the early 1990s, there was an increasing awareness that development methods, tools, and engineering management cannot be separated from each other and that all contribute to master the complexity of solutions. Important organizational changes were made, including the implementation of a multifunctional team organization balancing the long-term resources

| AIRCRAFT MODEL/TIME | DIGITAL TOOLS | DIGITALIZATION IN PRODUCT | ORGANIZATION |
|---------------------|--------------|---------------------------|--------------|
| **Draken** 1950s and early 1960s | Building own digital computer SARA to support engineering work Entering market of mini and mainframe computers | First airborne application of computers (analogue) Initial experiments with computers | Functional organization Pioneering director of calculations department External technology scouting DataSAAB is established |
| **Viggen** Mid 1960s | Analyses of the product surface, structure and aerodynamics | Introduction of a central computer for add-on functionality | Key individuals Founding principles avionics architecture formulated |
| **Continuously from early 1970s** | | Growing role of computers and information integration Decomposition into safety critical and non-critical applications | |
| **Second half of the 1980s** | Demonstrator system contributes to capability for digital flight control systems | Demonstrator system contributes to technology for digital flight control systems | Relatively small team of people masters overall system perspective |
| **Gripen A/B Second half of the 1980s** | Flight critical computer systems Distributed vehicle systems with limited integration | | External collaboration in global supply chain |
| **Early 1990s** | Complexity at a level where simulation and digital mock-ups are needed to master the product | New architectural approach to ensure safety-criticality Widely shared information based on data bases | Introduction of multifunctional teams and attention to several dimensions in the organization |
| **Gripen C/D Late 1990s** | Models and simulations for defining functional system requirements to meet extensive use of software in the product | Integrated system for control of vehicle systems More integrated functionality based on functional decomposition | Modelling and simulation enable teams to work together and support collaboration with external suppliers |
| **2000s** | Structured approaches based on standards to guarantee safety level | Continued transition to a larger portion of the product being software defined | Establishment of integration teams to find new ways of system integration |
| **Gripen E 2010s** | Approach combining MBSE, automatically generated code, virtual machines Multilevel simulation environment | Introduction of partitioned architecture Hardware independence Combination of resources for several levels of criticality in each computer | New capabilities for partitioned architectures Dynamic agile and frequently adapting internal organization with contributions from external actors |
and competencies, the shorter term project management supporting the design of the physical product, and the system focus. The changed conditions were reflected in the implementation of processes and tools for modeling, including the use of operational data to compare with simulation results and ultimately update the models. The increased formalization of the development processes aimed at managing criticalities such as product safety and security for the increasingly complex aircraft and its avionics system.

The Gripen architecture was based on decomposing the system into flight-critical systems (like the flight control system, enabling control of the aircraft that is unstable at subsonic speed), mission systems, and distributed vehicle systems with limited integration. Initial versions introduced external communication for tactical coordination, standardized computers, and high-level coding language. The multipurpose screens enabled integrated representation in the cockpit, offering opportunities to improve the pilot’s interface with the aircraft. At the same time, this pushed requirements for further functional integration. To reach the required safety level for the flight control system, a three-channel system was used. The overall architecture still represented a rather decentralized (federated) system containing modules as individual black boxes with independent computing resources.

### D. Gripen C/D – Expanded Functionality and Increasing Integration Drives Further Complexity

Further advances were made with the export versions of Gripen (C/D), which were developed in the second half of the 1990s. These aircraft included NATO compatibility, air-to-air refueling, multicolor screens, and improved computers and data buses. An integrated system for vehicle systems control was also introduced, enabling better health monitoring, initiation support, etcetera. The functionality became more integrated but still based on the earlier decomposition in modules. An ongoing trend of achieving more functionality with software fueled a continued transition to a larger portion of the product being software defined.

During the development of this generation, MBSE made important advances, including more functional modeling for state-based systems. Models and simulations started to make their way into defining functional systems requirements, facilitating work both internally and with external suppliers. In organizational terms, modeling and simulation increasingly supported a team’s ability to work together based on a better-shared understanding of the problem being addressed.

The continuously growing demand for integration and rapid introduction of new functionality increased the need for new approaches as the existing system integration approaches were not sufficient anymore. In response, several R&D projects were performed, and integration teams were established with the task of finding ways to achieve a new level of system integration while at the same time expanding the possibilities to be more responsive in the implementation of new functionalities. The new approach based on a platform with partitions was gradually introduced, first in a ground avionics demonstrator, a flying demonstrator, and finally in a less complex airborne product making the organization ready for the introduction into the Gripen system.

### E. Enabling Possibilities for Generativity and Criticality Control in the Gripen E System

Saab identified a possible step forward to a new level of system integration by building systems based on an approach combining MBSE with automatically generated code and virtual machines based on ARINC standards defining a partitioned architecture. The ARINC standards support avionics development by defining form, function, and fit characteristics of avionics, data communication standards, and disseminating best practices. They are widely used in the aviation industry. A partitioned architecture makes it possible to use the same resources such as sensors and computers for multiple purposes at different criticality levels. This enables containing the consequences of using generative data and solutions within a certain partition without effects on other partitions. It potentially allows for the use of generative methods and data for achieving critical functionality in safety-critical systems.

The Gripen E avionics system and the ways of managing the system aimed at enabling the continuous introduction of new functionality and flexible integration, both within the system and with external actors, while still maintaining affordability. The development organization is largely project-based with frequent changes and regroupings. To support the development, the new architectural approach using a platform with partitions enables the achievement of both hardware independence and the possibility to have several levels of criticality in each computer based on the ARINC standards supporting operating systems and compilers for partitioned system development. It also limits the need to test beyond the modules when updated as functionalities can be encapsulated to a larger extent.

The first version of Gripen E includes a wider range of sensors being more tightly integrated for various functionalities, enhanced communication systems, mentioned avionics architecture, and several aircraft improvements such as a more powerful engine and extended range. The Gripen E had its first test flight in June 2017, and the first aircraft was delivered in September 2019.

### V. Analysis

The narrative of avionics development at Saab shows that digitalization has been central to aircraft development for at least 50 years. The development of avionics represents an evolutionary path with step changes toward an increased reliance on digital technologies; first used in a sequence of initial experiments, then as add-on functionality in products, and later increasingly as an integral part of achieving critical functionality in systems. Currently, its use is focused on combining resources between add-on and critical functionalities enabling generativity and preparing for the increasing application of additional technologies such as artificial intelligence (AI) (see Fig. 1). In each of the eras, distinct organizational challenges could be identified. For instance, the initial experimentation era and subsequent use of add-on digital technologies represented incremental and modular challenges (cf. [13]). The transition toward digital technologies for achieving critical functionality reflects architectural innovation with its corresponding organizational changes. Finally, the architectural
solution to combine resources across add-on and critical functionalities constitute what Henderson and Clark [13] called radical innovation. Notably, this radical innovation was implemented in a product that had already existed in several previous generations.

The path toward increased digitalization is reflected in the (combined) product technologies, engineering methods and tools, and organizational design. Over time, the case of avionics, thus, shows an intricate entanglement of CoPS innovation aspects in terms of mastering complexity, organizational approaches, system integration, and architectures. The results show that engineering design tools, organizational approaches, and architecting approaches all contribute to mastering increasing complexity and benefit from new digital technologies. The analysis below addresses our overall research question in more detail, i.e., how CoPS firms navigate their approaches toward digital innovation over time.

A. Complexity and Systems Integration

Avionics are complex systemic products building on a multitude components, skills, and knowledge and can be considered to exceed the complexity of many other CoPS systems, such as flight simulators, that have been studied in previous studies addressing embedded software [2]. The case of avionics represents a clear account of how a CoPS firm navigates its approaches toward digital innovation over time in such an extreme context. The narrative stresses the evolutionary nature of digital transformation, including combinations of what could be considered game-changing landmark innovations and more continuous innovations. Over time these have been contained within a framework of fundamental principles that, together with the modular functional decomposition of avionics, demonstrate stability at the avionics level, but based on varying integration and organizational strategies over the years have evolved into an expanding architectural platform approach. Initially, upgrades were driven by the availability of increasingly powerful computers but have refocused into upgrades enabling innovation and generativity for an expanding variety of functionality and integration, including safety-critical and nonsafety-critical applications. The case of avionics illustrates how CoPS innovation contexts are emergent and situated, something which has been argued to be one of the grand challenges for future innovation management [12]. Previously, scholars have pointed at the necessity to manage performance tradeoffs [10] and organizational and operational tensions [2]. The implications for the design of CoPS with embedded digital solutions have not been so clearly outlined in the literature.

In early avionics development (before the 1990s), it was still possible for key individuals to understand the complete systems. The case illustrates a reliance on key individuals. One of these was Börje Langefors and is attributed with the origin of the information systems research field [69]. The case also clearly shows how digital solutions in the product took complexity to such a level that formalized methods were needed in product development. Certain digital solutions, such as multipurpose screens for integrated representation pushed requirements for further integration of functionality, thereby adding even more complexity.

The study shows that complexity is mastered through system integration as an increasingly combined and intertwined approach based on architectural solutions, digital system engineering tools, and organizational designs. The different eras of integration of digital technologies highlight some distinct properties of systems integration. Each era represents a level of integration that may coexist within partitions of the same complex system, reflecting a need for different systems integration strategies for different partitions of the system. This contrasts with the more linear bottom-up maturation of a technology in the sense that an upgraded technology may be integrated following a range of avenues depending on how integrated the use of the upgraded technology. Previous research has paid attention to the emergence of digital system engineering tools, sometimes referred to as formal or rational tools [2]. Existing research has also pointed at the risk of an overreliance on these tools and stresses the importance of management discretionary and more informal approaches (e.g., [2], [70], [71]).

Our study provides important complementary evidence on how reliance on these approaches is combined and balanced with
additional organizational approaches as well as with solutions in the product architecture. With the digital transformation, such a combined approach has not only become possible but also essential to harness CoPS complexity beyond the scope of what a single human can understand.

B. Organization and Architecture

The importance of the system architecture has been acknowledged in several previous studies in the field of CoPS and often connected to the type of knowledge necessary for CoPS development over time [14], [34], [35] and the corresponding organizations in which these CoPS systems are developed and operate [21]. Recently, Tamburri et al. [72] have argued that future software-based systems require perpetual interaction and feedback across organizational and technical structures implying a dynamic mirroring between organizations and system architectures.

The literature on digital innovation has also noted that layered architectures have emerged with the rise of digital technologies [20]. The case of avionics provides a detailed account of the emergence of the product architecture in combination with its organization. It can be described as continuous development and upgrading of avionics from the 1970s onwards. The principles that were defined early on to be able long-term address the safety-critical nature of the system have remained important over time. The use of a central computer for information sharing in the Viggen was initially based on the concentration of all information. Later, this evolved into modular architectures that integrate several computers with data buses focusing on sharing relevant data. The combination of modularity and integration has evolved further in the most recent system architecture that builds on an approach combining a platform and applications that are separated partitions supported by the operating system. They reflect the layered systems architectures as described in the literature on digital innovation [20]. Compared to this literature, however, our case points at the centrality of the safety-criticality dimension in the architectural approach. In the latest version of the Gripen aircraft, the partitions fulfill a specific role to strictly separate safety-critical and non-safety-critical functionality while still combining resources. This reflects the intention to create a system that is more than the sum of its parts already at architectural level, in contrast to modular architectures that focus on independent parts rather than the sum.

With the emerging requirements for the further integration of functionality, the accelerating development of digital technologies and dynamically evolving conditions, the architectural approach is focused on simultaneously being able to address the need for safety-criticality and enable generativity in the system. Development is no longer a single development responding to a set of static input, but rather a continuous adaptation of a system to respond to evolving needs, conditions, and technical possibilities. Consequently, our study provides a detailed account of how architectural and organizational approaches contribute to the development of safety-critical CoPS systems. It further highlights the evolving characteristics of architecture over time. Neither the architecture, nor the role of the architecture is static but rather adapts to new conditions and expectations, acting as a carrier of evolving functional integration. While scholars in the field of digital innovation have argued that the understanding of digital innovation needs to build on the innate characteristics of digital technologies [20], [46], [73], the study of avionics additionally shows that, for CoPS, also the wider system conditions and characteristics play an important role.

The case provides additional evidence for organizational approaches used in CoPS innovation in terms of the continuous integration of the emerging digital solutions in a wider inter-organizational context. This is not least exemplified by the pioneering employee Langefors’ initial explorations related to the state-of-the-art of digital computers in the US and Sweden’s national context in the 1950s. This openness for external solutions was initially carried out by individuals but was later more formalized in for instance the Gripen development where new conditions forced an extensive effort to build and utilize a global supply chain. Still, the aircraft largely defined the organization. For each new model and generation, the whole organization was focused on getting the aircraft ready for the first flight in an almost self-organizing way. The context was characterized by one aircraft, one organization, and one customer. Later, the increased complexity in the product as well as in terms of more customers, aircraft models, and inter-organizational collaborations was met by an organizational transition in terms of, e.g., the establishment of integration teams and the use of digital tools. These empirical observations expand previous insights on the mirroring relationships between organizations and system architectures (e.g., [13], [21]) and provide a clear account of “breaking-the-mirror” or perhaps even a situation beyond mirroring. This is perhaps most obvious when systems become more integrated due to the need for overarching functionalities supporting ease of operation and health monitoring. This results in increasing entanglement of many functions in the aircraft. Such complexity may be difficult, if not impossible, to mirror in the organizational perspective. The case points at a potential new insight, i.e., that digital system engineering tools may have a role in bridging the relationships between organizations and system architectures and complement the organizational mirroring in CoPS contexts. Consequently, the current understanding of CoPS firms as project-based organizations [38] appears as insufficient when complexity has surpassed human cognition and organizations and architectures are increasingly entangled.

The observations from the avionics study and their implications for CoPS innovation aspects when CoPS are increasingly based on embedded digital solutions are outlined in Table IV. Based on the findings and analysis, several implications of the embeddedness of digital technologies in CoPS are discussed and future research avenues are outlined.

VI. FUTURE RESEARCH AVENUES

Based on the findings and analysis, several implications of the embeddedness of digital technologies in CoPS are discussed and future research avenues are outlined.

A. Avenue 1: Generativity in Safety-Critical Systems

Platforms and ecosystems are frequently discussed in relation to digital innovation and digital systems [20], [46]. While
platform-based approaches were initially explored as internal or supply chain platforms [24] there is an increasing focus on platforms as a new way of organizing within a large network of actors in an organizational ecosystem [22]. It appears that the main rationale for platforms in IT and mobile technology is the ability to master the combination of market control and generativity [49] while for CoPS industries we find the rationale to be an ability to master the unique combination of system criticality and generativity.

Disregarding the perspective, platform-based approaches are flexible, scalable, and facilitate generativity in the context of digital solutions. Seldom though, generativity has been discussed in relation to properties such as safety-criticality. In the case of avionics, but also in other CoPS systems and infrastructures, the importance of safety-criticality is evident. In avionics, digital innovations have substantially contributed to increased safety.

System-building industries providing CoPS, such as those in the aviation industry, have long-faced distinct challenges related to complexity and systems integration. It appears that these firms can use architectural and organizational strategies to deal with a multitude of criteria. In the face of the emerging focus on platform-based approaches and attention to generativity, it is necessary to explore, in a wider context, how generativity can be achieved in safety-critical systems through, for instance, architectures and boundary objects bridging the incomplete or broken mirroring. While generativity tends to rely on flexibility, openness, and scalability, safety-criticality is normally addressed by a high degree of control. A further understanding of how these can be achieved simultaneously in CoPS systems is necessary to capture the benefits of digital technologies in these systems. This is important as digital technologies are becoming increasingly intelligent and are expected to play an even more important role in most CoPS.

B. Avenue 2: Complexity Beyond Human Cognition

Over time, complexity in the aviation industry, in an aircraft, but also in subsystems, has grown and is surpassing human cognition. Other CoPS firms face similar challenges related to complexity. Garud et al. [74] have stressed the importance that the innovation management discipline needs to understand approaches that can help harness and master complexity. Initiatives like MBSE are visible in practice, such as in our case of avionics, but its consequences for organization design have hardly been captured in the literature on innovation management and organization. MBSE can be understood as what Carlile [75] refers to as “boundary objects,” serving to represent different functional interests and facilitating their negotiation and transformation in product-development settings. MBSE utilizes increasingly complete boundary object representations, covering not only solution aspects and functionality but also the available design space and requirements management. This represents a wider ongoing transformation in system engineering and software engineering toward an expanded rationality, where more actors can contribute with informed perspectives. The managerial implications of what could be referred to as intelligent boundary objects beyond representation and rather as an active part in the interaction are still largely unaddressed. This article indicates that such boundary objects tend to change the role of organization and management. Further research could explore this in-depth by focusing on the use of such boundary objects for instance in relation to (bounded) rationality and/or generativity in decision-making approaches.
C. Avenue 3: Intelligent Boundary Objects Spanning Architectures and Organizational Design

In comparison to modular architectures that have been studied frequently [34], [36], [76], layered modular architectures have distinct characteristics [20]. Often, a particular range of layers functions as a new product in terms of a platform, on which other actors can also innovate when combined with an enabling organization and business model. The external actors can seldom be directly controlled; rather, an organization needs to develop a capability to maneuver and navigate [31], [77]. In CoPS industries, however, the incentives to be part of the ecosystem differ from IT and mobile technology contexts and are characterized by high entry barriers, low volumes, but also lower risks of imitability and, therefore, high potential long-term value.

The implications of layered architectures in CoPS can only be understood by studying technology and management aspects jointly and requires a new understanding and conceptualization of CoPS project-based organizations. In future CoPS, it is particularly important to understand the relationship between systems architecture and organizations in a multifaceted way. In this context, new perspectives on the links between system architecture and organizational design are needed. As scholars have previously argued, a direct reflection of the architecture and the organization can become a trap that prevents disruptive innovation [21]. It appears that intelligent boundary objects can handle cracked mirrors and enable integrative perspectives to deal with a multitude of criteria. Further research needs to provide additional insight into future mirroring principles for organizational design, intelligent boundary objects, and interactions in ecosystems that allow for a dynamically changing, yet partly predictable pattern.

VII. CONCLUSION

In recent years, current digitalization trends and their consequences have become a major focus in research on innovation management [78]. Yet, insights into how digital innovation processes unfold in practice – especially in industrial contexts and CoPS – are scarce [73]. A detailed narrative account of avionics development since the 1950s describes the transitions in the product, the organization, and the design approaches, refining what Hobday and Brady [3] refer to as software engineering diffusion into CoPS. The case illustrates that the digital transformation in CoPS subsequently enfolds in step changes representing a sequence of initial experiments, add-on functionality, an integral part of achieving critical functionality, and currently combining add-on and critical functionality enabling generativity. Each of the eras represents levels of systems integration that could coexist also at one point in time, but with distinct organizational challenges, reflecting elements of incremental, modular, architectural, and radical innovation [13] and in the relationship between product architectures and organizational design a mirror that can be considered as cracked or broken [21].

The findings extend previous research by emphasizing the evolution of the intricate relationships between the systems architecture and organizational approaches when digital technology not only enables but also enforces increased complexity, expanded functionality, increased systems integration, and continuous development. They also stress dependencies that are nested and accentuated by the complexity that has emerged beyond human cognition, where increasingly sophisticated boundary objects based on modeling, simulation, and data play an important role in the organization’s ability to design and operate the system. These boundary objects relate as well as decouple the multifaceted dynamic relation between organization and architecture beyond the current understanding of mirroring. The results also extend existing perspectives on platform strategies to resolve tensions between generativity and (market) control, and point at the importance of criticality control, not least as generative digital technologies may be central in achieving critical properties such as safety. This article contributes to the CoPS literature and the literature on digital transformation by extending its perspective and bringing the characteristics of digitalization into the CoPS domain. Based on the new insights, several avenues for further research and theory building are outlined, including design organizations that can harness tensions between criticality and generativity, complexity beyond human cognition, and intelligent boundary objects spanning systems architecture and organizational design.

It is expected that many of the benefits of digital technology will emerge in complex systems, including critical societal infrastructures. Hence, it is imperative to understand digital transformation and digital innovation, including its enabling and enforcing nature, in a CoPS context. Looking even further beyond the inclusion of digital technology and considering current developments in the AI and autonomous systems domain, there is still limited knowledge on how existing organizational logic is affected as systems become increasingly intelligent [79]. This opens an exciting field of research with potential further studies that are expected to benefit from combining deep insights on existing technology-oriented AI research with management research and that build on the close connection between technology and management to unravel the likely implications for complex intelligent systems emergence.

The study of complex systems requires a deep contextual understanding. We could not have captured the insights on avionics development and intricate linkages between the different aspects without deep embeddedness in the empirical context. Our rather unique approach based on deep interaction between researchers and practitioners (cf. [54], [80]) and additionally extensive historical archival accounts documenting the organizational memory (cf. [68]) has enabled us to capture the emergence of digital innovation and the digital transformation of CoPS over time. Despite the contributions and deep insights provided, a limitation of the presented research is that only one specific CoPS system is addressed in this article. Although we argue that the avionics case represents many of the characteristics that can be found in CoPS contexts (cf. [2]), and that the article, thus, answers the call for new insights on the multifaceted aspects of the digital transformation and innovation management [81], further studies of additional CoPS and critical societal infrastructure are necessary to validate the results and shed additional light on the digitalization of CoPS.
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