DIGITAL INNOVATION IN COMPLEX SYSTEMS- MANAGING CRITICAL APPLICATIONS AND GENERATIVITY

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Abstract

Digital technology is increasingly integrated in industrial applications and alters existing system architectures and innovation processes. This paper is based on a case study of avionics at the Swedish firm Saab Aeronautics. The results combine management and engineering perspectives and show how system partitioning enables control and generativity priorities in complex systems.

1 Introduction and Purpose

Firms providing complex products and systems, such as in the aviation industry have since long faced distinct challenges related to complexity and systems integration and the simultaneous consideration of properties such as safety, security, reliability and cost. In order to address these challenges, they traditionally rely on relatively rigorous innovation processes guided by regulatory involvement that may stipulate working approaches and certification [1] Regulatory bodies may control and influence innovation for several reasons, related to e.g. safety or the need for international standards. For instance, to make sure that software will perform reliably in an airborne environment, extensive guidelines exist in avionics software development (e.g. DO-178B) that are stipulating approaches, e.g. through system safety classification, objectives, and independencies. Generally, critical applications require rigorous and controlled innovation approaches.

Simultaneously, one of the central opportunities related to an increasing integration of digital technology is generativity. Generativity refers to the dynamic and unbounded aspect of digital innovations to stimulate continuous innovation often driven by a body of largely uncoordinated actors [2] Generativity builds on systems with built-in flexibility, e.g. platform-based and layered systems and applications. System criticality and generativity are central to future technology development but will also be widely shared challenges in management and organizational approaches for innovation in complex systems.

In order to explore important aspects and approaches related to the management of critical applications and generativity in innovation processes, the current paper focuses on an in-depth empirical study of avionics development in the aviation industry. The purpose is to explore how simultaneous demands on criticality and generativity are addressed in the systems architecture and related management and organizational approaches for digital innovation in avionics development.

2 Theoretical background

2.1 Digital innovation

The rise of digital technologies has opened up new opportunities and transforms the nature of innovation and its management and organizational challenges [2, 3]. A new landscape of innovation is emerging, including the consideration of different types of architectures, the emergence of technology platforms, and new organizational approaches crossing traditional industry boundaries and relying on external actors [2, 4, 5, 6, 7].

Established industrial firms are currently transforming their innovation strategies and processes to embrace digital innovation [8, 9]. It has been argued that digital innovation requires the management of different concerns simultaneously, regarding e.g. capability (existing versus requisite), focus (product versus process), collaboration (internal versus external), and governance (control versus flexibility) [9]. Despite this increasing interest, existing research only provides partial explanations of why and how different concerns emerge, and more importantly, how they can be addressed. In addition, existing studies on digital innovation have focused mainly on newer or emerging industries in e.g. the information technology business, with firms as Google and Apple in focus [e.g. 10]. Some evidence is available based on studies of industrial firms focusing on how these firms engage in the design of smart products, i.e. through the inclusion of digital but often still non-critical components in traditional products [e.g. 3, 9, 11, 12, 13]. A growing body of research is emerging, but further in-depth empirical studies can outline the specific challenges faced by different types of industrial firms.

2.2 System criticality

Issues related to system criticality are hardly addressed in the current innovation management literature. Yet they can have major implications for the innovation approaches used [14]. Current developments related to IoT and industrial control systems represent an expansion into domains of critical applications where e.g. safety and security are imperative [15, 16]. Industrial and scholarly voices agree that these properties will even gain in importance when architecting systems [15, 17]. The development of critical systems often is dictated by high demands based on certification and compliance to standards that are stipulated by regulatory bodies, core organizations are normally obliged to retain or prove total control of the system [14]. This would include ensuring that the system functions in nominal, but perhaps even more challenging in off-nominal conditions [18].

2.3 Generativity

Existing research on digital innovation largely builds on the premise that innovation gains are generated by creating conditions for generativity. Generativity may concern further continuous innovation at the firm-level or in a firm’s network, i.e. different types of uncoordinated actors. Generativity is widely perceived to be enabled by platform-thinking [2, 19]. A technology platform is a foundation of a technological system to which firms can develop complementary products, technologies and services [20]. It has been argued that digital technology platforms are central to digital innovation as they bring together different technology affordances and previously separated user experiences by enabling other firms to invent novel components such as new applications with which its basic functionality can be expanded. A digital product platform including its applications typically encompasses a, to some extent, flexible system, based on a particular range of layers that can function as a new product, but simultaneously enable others to innovate upon [21].

2.4 Innovation patterns for generativity and criticality

Approaches to achieve generativity and control for criticality build on stark contrasting innovation patterns. Generativity implies a move towards increased openness to create possibilities for other actors in a firm’s periphery to innovate. Despite advantages, this also complicates the control of innovation by these peripheral organizations [6, 19]. The issue of control has been discussed in relation to the competitive dynamics in the industry and market adoption, i.e. how core organizations can incentivize and align peripheral organizations to act in ways that are enhancing the platform and prevent platform-competing behavior [19, 22]. However, control in relation to system-criticality is less well addressed in this literature. Several approaches to control have been discussed, including sharing Application Programming Interfaces (APIs), mechanisms to induce trust as well as power [23] and platform access regulations [22]. The simultaneous demands on criticality and generativity seem to be opposite forces. While generativity makes innovation processes and their outcome difficult to control [22, 24, 25, 26, 27], criticality requires control through rigorous and stipulated approaches. for criticality and generativity represent opposed forces. The question remains how criticality and generativity can be supported simultaneously in a systems architecture and the related management and organizational approaches.

2.5 Mirroring – technology and organizational links

The relationship between technology development (e.g. related to systems architecture) and the organization has been discussed in different fields of literature. In software development, Conway's law describes that a software's interface structure often reflects the organizational structure as a software module can be considered as the result of the communication of multiple authors that are bounded in their communication by the organization structure they are part of. In the organizational literature, this phenomenon is described as the "mirroring hypothesis", i.e. organizational ties will correspond to the technical dependencies in the work being performed [4]. More recently, and especially in relation to systems consisting of physical and digital components, it has been suggested that a new type of relationship between the system architecture and the organization is emerging. When innovation takes place outside the boundaries of a firm strict mirroring can become a trap. Rather, firms need to adopt strategies such as partial mirroring and breaking the mirror and build on core-periphery organizational structures [4]. This type of mirroring could potentially help to address several of the challenges faced in the aviation industry related to a transformation in design perspective from "divide and conquer" to "conquer and divide" [28]. In order to understand this further in relation to how criticality and generativity can be supported simultaneously, we pay specifically attention to mirroring aspects.

3 The case of avionics at Saab

The aviation industry has faced rapid technology development in avionics systems for several decades. Currently, the most recent avionics systems are based on the principles of DIMA, with a common platform on which the applications run in several partitions [see e.g. 29]. This represents a strategy aiming to meet the future demands and possibilities related to digital innovation in the aviation industry. However, the emergence of avionics and how platform-based strategies were shaped date back in time. At Saab, avionics development and related approaches can be traced to the 1960s. We have captured the progress and strategy adaptations made by Saab to achieve criticality in combination with expanding functionality, flexibility and possibilities for increasing future generativity of the system. Table 1 provides an overview.

3.1 Early avionics development

Avionics development at Saab dates back as far as the second half of the 1950s when the first digital calculator applications were considered. During the 1960s, in the last versions of Saab's supersonic aircraft Draken, an on-board computer was introduced which was combined with an analogue electro mechanical presentation system. A new aircraft, Viggen, was introduced by Saab in the late 1960s, and contained a general-purpose computer. This computer system contributed to several functions such as navigation and landing and was recognised as highly increasing the aircraft functional performance. However, still the design philosophy at Saab was to ensure safe flying and manual control of the aircraft without dependence on digital computers. [30]

Table 2 Saab Aircraft avionics progress over time

Aircraft	Avionics progress	Time
Draken	First airborne application of computers	Early 1960s
Viggen	Introduction of a central computer and integration	Late 1960s
	Decomposition into safety critical and non-critical application, where computers were not handling safety critical functionality	Late 1960s
	Continuously growing role of computers and information integration	Continuously from early 1970s
	Flight critical computer systems enters for e.g. flight control systems	Second half of the 1980s
Gripen A/B	Use of data buses and glass cockpits	Second half of the 1980s
	Complexity taken to a level where formalized methods are needed to master the product	Early 1990s
Gripen C/D	Integrated system for control of vehicle systems	Late 1990s
	A continued trend of achieving more functionality with software fuels a continued transition to a larger portion of the product being software defined	2000s
Gripen E	Increasing demand for generativity and control leads to application of Distributed Integrated Modular Avionics (DIMA)	2010s

3.2 Increasingly integrated system and use of computers

During the life of Viggen, the avionics systems evolved, and additional functionality was introduced as computer resources, experience and knowledge became increasingly available. The aircraft was gradually becoming a system aircraft where systems were increasingly integrated. This integration offered possibilities to offload work from the pilot. Late in the Viggen program, during the 1980s, technology development was achieved through a demonstrator with an electronic flight control system. This paved the way for the use of computer systems for flight critical applications and fly by wire replacing manual flight controls in the next generation of aircrafts (the Gripen system). Despite these advancements, still, a relatively small team of key individuals was able to master the overall aircraft system.

3.3 Emerging complexity and increased reliance on software

The Gripen system (successor to the Viggen system) and Saab 340 (a commuter aircraft) were developed in parallel during the 1980s. These products included glass cockpits and avionics in a set of computers. Software played an increasingly important role. The Gripen architecture was based on the decomposition of the system into flight critical systems, mission systems and distributed vehicle systems with limited integration. Initial versions of Gripen introduced external communication for tactical coordination, standardized computers and the use of high level language for coding. In addition, the multipurpose screens enabled integrated representation in the cockpit that offered possibilities to improve the pilot's interface with the aircraft. At the same time, this was driving requirements for further integration of functionality.

With the development of the Gripen system, the complexity had reached such a level that a single organisation could no longer host all needed competencies. The complexity of solutions made it impossible for a single human to understand, analyse and develop a system. Therefore, a more formalized approach was needed, leading to intense organizational changes and development at Saab (e.g. multi team organisation and focus on integration teams), and the implementation of processes and tools e.g. for modelling and simulation from the early 1990s.

3.4 Formalization of criticality management

The increased formalization of the development processes at Saab aimed at mastering criticality aspect such as product safety and security for the increasingly complex aircraft and the avionics system. The resulting development methodology aimed to support active design decisions to arrive at a design that was well-balanced in terms of risk and consequences and that was meeting the system requirements. This included architectural approaches such as use of redundancy, functionality monitoring and surveillance, dissimilar components and consequence minimization. The development methodology also includes formal methods for verification. In addition, the complexity of the aircraft system also requires supplementary modelling and simulation with specific attention to interfaces. The resulting development process is based on international standards for meeting, for instance, justification levels. One of the standards that emerged in the industry and was applied is the standard RTCA DO-178B, Software Considerations in Airborne Systems and Equipment Certification. This has become a wide-spread foundation for the development of safety critical systems software within the aviation industry [31]. The standard relies on a structured management process enabling the use of tools and methods. The standard utilizes *classification* of systems by assigning different safety levels, from A to E, reflecting the safety impact they have, see table 2. Systems that may cause a catastrophic failure are assigned to Level A. Levels B to D reflect a decreasing safety impact while systems with no safety consequences are assigned to Level E. The latter level is excluded from this standard as it has no safety implications. The standard is not a development process, but rather a structured way of organizing the assurance of safety. In addition, the standard uses *objectives* throughout the life cycle within e.g. planning, development, QA, certification and with an emphasis on verification. One example of an objective is to maintain traceability from high level to low level requirements. A further approach applied in the standard is *independence*, meaning e.g. that there is a separation of responsibilities between the individuals performing a task and the individuals reviewing and/or approving the outcome. The standard also prescribes that the involved people and organizations must be authorized. The standard is formulated for Level A systems where all objectives and independencies are mandatory. The standard also defines what relaxation of objectives and independencies for Level B-D is allowed. In the aviation industry, the design organization must continuously demonstrate to certifying authorities that they meet the objectives to gain airworthiness and maintain it. A wide range of methods, tools and equipment are normally used to achieve this, e.g. requirement management tools, fault tree analysis, model-based systems engineering, simulations and test rigs.

Table 2 Safety approach in software development in avionics

Safety level	Failure condition	Objectives	Independencies	Failure Rate
A	Catastrophic	66	25	10−9/h
B	Hazardous	65	14	10−7/h
C	Major	57	2	10−5/h
D	Minor	28	2	10−3/h
E	No Effect	0	0	n/a

3.5 Continued trend of increased functionality using software

In relation to these developments and compliance to international standards, further steps were taken for Saab's export version of Gripen (C/D) which was developed in the second half of the 1990s. In this version, an integrated system for control of vehicle systems was introduced, enabling better health monitoring, start-up support etcetera, but also creating a functionality that is more integrated. The continued trend of increased functionality using software has fuelled a further transition into a larger portion of the product being software defined. Model-based development took important steps forward, including more functional modelling, e.g. for state-based systems. Over time, the C/D system has been continuously updated with new functionalities that have been integrated in the system. Examples include the introduction of helmet mounted displays and new payloads which enables Saab to maintain up-to-date capabilities in their aircrafts.

As avionics has become a substantial portion of the development cost for new aircraft versions, the growing demand on integration and rapid introduction of new functionality raised the need for new ways to deal with the avionics and software development. A possible step forward was identified to build systems based on model-based systems engineering with automatically generated code, virtual machines enabling hardware independence and the possibility to combine several levels of criticality in the same computer. This concentrates the need for testing to the updated partitions and their integration into the overall system. These technologies have been gradually introduced based on initial studies and experiments that served as the basis for an avionics rig, a ground-based system simulator with real hardware, followed by airborne demonstration programs and other R&D projects. The first product application was the airborne avionics for a smaller unmanned system.

3.6 Growing demand on generativity

Saab's latest development of the Gripen E is based on the identified avionics approach described above. In order to address growing demands on generativity, the core of the architecture is based on a DIMA architecture. This architecture combines several physical computers into one logical entity and allows time and safety critical applications to be run flexibly on the underlying hardware together with non-safety critical applications. In this way, the Gripen E establishes an avionics system and an approach to manage the system that is aiming at enabling continuous introduction of new functionality and flexible integration both within the system and with external actors, while still maintaining affordability.

4. Discussion and Conclusions

Studying the case of avionics in an industry that has been long characterized by innovation with a focus on control for criticality and more recently to an increasing extent on generativity may help to outline and address the future challenges of digital innovation in the aviation industry but also in other industrial contexts. Below, we outline some implications related to our study.

4.1 Mirroring and beyond – technology and organizational links

As digital technologies emerge, the number of digital and mixed systems is growing, and the number of purely physical systems is shrinking. The increased role of digital components and software defined functionality is creating new challenges related to the interplay between physical and digital parts, but also the organization and management not at the least in relation to complexity. Colfer and Baldwin [4] have suggested that this requires new approaches to the links between technology and organization. Rather than strict mirroring, partial mirroring, based on enabling generativity by actors in a firm's periphery can be the recommended strategy. The case of avionics at Saab shows that this requires careful strategic choices related to the systems architecture as well as new organizational and management approaches. The DIMA architecture reflects generally higher levels of flexibility and adaptability but also creates organizational challenges. Based on the results, we conclude that technology and organizational aspects need to be considered integratively. Major questions need to be addressed when complexity is emerging beyond human cognition, e.g. (1) How can complex digital innovation be organized? (2) How do organizational approaches need to evolve dynamically over time, and (3) what are the competencies that future engineers need to master to architect systems that support criticality as well as generativity.

4.2 Evolutionary refinement to manage criticality and generativity

We also note that digitalization has been central to aircraft development during at least fifty years. Compared to some perspectives on digitalization that present it as relatively new causing rethinking of our underlying assumptions about innovation [6], the case of avionics represents an evolutionary path towards increased digitalization. This evolution includes combinations of disruptive and continuous innovations contained within a framework of fundamental principles that demonstrate remarkable stability and are supported by expanding architectural approaches. Novel technologies such as machine learning and big data analytics suggest that these types of systems will continue to evolve with a rapid pace and require new and additional approaches to benefit from such technologies.

Central to the evolution of avionics at Saab have been two main principles [30]:

1. *The use of a central computer for information sharing*, initially based on concentration of all information, later by architecting modular architectures that integrate several computers with data buses focusing on sharing relevant data. The combination of modularity and integration is further evolved in DIMA-based systems.

2. *The division between safety critical and non-critical systems*, initially during the 1960s building on the idea that flight safety could not be dependent on computers. Twenty years later, during the 1980s, avionics had reached such a maturity that safety critical systems could be based on computers and electronic flight control systems were introduced both in civil and military aviation. These systems were strictly separated from less critical applications. An important part of the studied DIMA architecture is the use of partitions where different partitions can have different levels of safety, which allows some parts to become increasingly open and based on third party solutions.

The functional decomposition of the system remains rather stable at avionics system level, while different modules or functionalities evolve both in continuous and disruptive ways (e.g. mechanical to electronic flight control systems and new navigation technologies). The long life cycles of aircrafts, combined with the rapid development of computers has resulted in continuous development and upgrades of avionics from the 1970s onwards and is still an important strategy of aircraft manufacturers. Initially upgrades were driven by the availability of increasingly powerful computers but has refocused into functional upgrades. The recent transformation to DIMA represents an architectural innovation [32], that is incremental from a functional decomposition perspective and disruptive in terms of process and execution platform focusing on the way modules are integrated and scale to an evolutionary system. This type of architecture potentially provides prerequisites to address criticality and generativity simultaneously.

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