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Software-defined Automation in Industrial Production: Drivers of Transformation

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Abstract. Increasing market uncertainties and the growing demand for customized products from end-users are creating major challenges for manufacturing companies, driving the need for a production system automation that offers greater flexibility and adaptability to remain competitive and sustainable. However, current highly automated production systems are typically designed to be static, hardware-centric and difficult to scale and reconfigure quickly. Consequently, it affects the ability of manufacturing companies to continuously adapt to changing customer requirements. Using a case study method, this paper identifies the challenges of traditional hardware-centric automation and analyzes the key drivers for the adoption of software-defined automation (SDA) in production systems. The study identifies system rigidity, hardware constraints, and vendor lock-in as critical challenges of hardware-centric automation. The research reveals that the key drivers for transitioning towards software-defined automation are system flexibility and technological integration, operational efficiency and cost reduction, and enhanced sustainability and cybersecurity. This study contributes to existing literature on SDA in industrial production by providing empirical evidence and identifying SDA as a potential approach to mitigate the challenges of hardware-centric automation.

1. Introduction

Amid unpredictable market conditions, manufacturing companies often face challenges in adapting their production systems to manufacture products with shorter life cycles, high variety, and low volume. Today, customers are demanding customized products from manufacturing companies [1]. The growing customer requirements coupled with uncertain market conditions forces manufacturing companies to have production systems that are both highly automated and adaptable [2]. However, manufacturing companies often lack highly automated production systems that are flexible, adaptable, and scalable, making them rigid and complex to efficiently meet rapidly evolving consumer needs [1–3]. For instance, when new product variants are introduced, the changes in running production often come with costly upgrades, longer lead times and equipment becoming obsolete even if it is still functional, simply because it can no longer meet new requirements [4]. This is because in highly automated production systems, hardware and software are often tightly coupled, resulting in a hardware-centric approach in automation [3, 5]. This approach restricts flexibility, adaptability and scalability in these systems, thereby making reconfiguration difficult. Consequently, manufacturing companies struggle to stay competitive, cost-efficient, and sustainable [1–3].



One approach that contrasts hardware-centric approach is the concept of software-defined anything (SDx), shared by Lechler and Verl [3] in which system functionality is decoupled from hardware and managed entirely through software. As a result, hardware and software are no longer tightly coupled and dependent, reflecting a fundamental change in the design and development of highly automated production systems. Prior research suggests that shifting operations from hardware-centric to software-defined offers several advantages. For instance, Barwasser et al. [1] presented a method for the development of software-defined manufacturing equipment to enhance performance of the production facility. Grimmeisen et al. [6] highlighted that SDx supports the development of flexible and self-configuring production systems. This study presented a new approach that enables automated and continuous risk assessment of software-defined robotic systems. Frick et al. [7] introduced software-defined control cabinet architecture to overcome limitations of control cabinets for enhancing adaptability and reusability. Vettermann and Röper [8] elaborated on the role of software-defined automation (SDA) combined with artificial intelligence (AI) in shaping future production and lowering system administration costs. Pang et al. [9] discussed the application of SDx paradigm in automation and shared a development framework for software-defined automation and control.

Although the adoption of SDA could offer novel opportunities and benefits to the manufacturing industry, current studies primarily focus on technological components, architectural foundations, and development frameworks, leaving a gap in understanding the organizational and strategic drivers behind SDA adoption. This lack of attention to non-technical factors limits our understanding of how companies can successfully implement SDA beyond technology. Moreover, without addressing these aspects, the practical realization of SDA's potential remains uncertain. Therefore, it is vital for manufacturing companies to explore specific challenges of traditional hardware-centric automation and drivers for SDA. Accordingly, the purpose of this study is to examine the challenges of traditional hardware-centric automation and analyze the key drivers for the adoption of software-defined automation in highly automated production systems.

2. Theoretical Background

2.1 Traditional Hardware-centric Automation in Manufacturing

Automation in Production Systems is the utilization of technologies for automating manufacturing tasks with an objective of maximizing operational efficiency with minimal human intervention [10]. The key technologies that are used in automation include programmable logic controllers (PLCs), robotics, sensors and actuators, industrial IoT devices, and industrial networks [10, 11]. Among these technologies, PLCs play a central role within highly automated production systems by executing the control logic that governs how automated tasks are performed in production. The subsystems in highly automated production systems such as automated welding stations or assembly cells are controlled by a dedicated PLC [12, 13].

In accordance with Ahn et al.'s [5] article, hardware-centric automation refers to the traditional approach in industrial automation of production systems where the control logic and operational capabilities of machines are tightly coupled and constrained by the specific hardware. In hardware-centric automation, the manufacturing functions of a highly automated production system are fully embedded into physical devices such as PLCs making them fixed and task-specific [5]. For example, an automated welding station uses a PLC to control the welding process, directing the robot's arm where and how to perform the welding spots [13]. In this case, the robot's movements are controlled by the software on the PLC which is tightly coupled with the

hardware. This strong coupling introduces limitations in highly automated production systems. Although PLCs involve software, the term hardware-centric automation in this study refers to systems where software functionality is embedded and constrained by specific hardware, creating rigidity [3, 5]. As noted by Ahn et al. [5], hardware-centric approaches in manufacturing limits flexibility and adaptability to changing production requirements and demands. When components change or new product variants are introduced or tasks need to be modified in the same welding station, the PLC program must be reconfigured on site by the experts resulting in extra time and effort [13]. Moreover, any maintenance tasks that require changes or updates in the PLCs may require production stoppages which can cause extra time consumption [12, 13]. Consequently, any changes to the system would require on-site adjustments typically involving a change of hardware or manual reprogramming [3].

In addition, current highly automated production systems are traditionally designed to be static with limited memory capacity and processing power and are often connected to specific vendors [14, 15]. Bibl et al. [14] explains the vendor lock-in issue with an example, stating that most of the robot manufacturers develop vendor-specific control hardware which is tightly coupled with robots. These limitations hinder the integration of advanced digital technologies, such as artificial intelligence [16], restrict interoperability [17], scalability [18], and reconfigurability [3]. Given these challenges, traditional hardware-centric automation in manufacturing must not only operate efficiently but also need to incorporate characteristics such as greater flexibility, adaptability, and scalability to cope with rapidly evolving market needs.

Flexibility refers to the ability of a highly automated production system to resiliently adjust itself to the short-term production changes without demanding extensive downtime and reconfiguration [19, 20]. Adaptability means the ability of the highly automated production system to respond effectively to broader changes in production such as new product introductions or shifts in market demand that may not require reconfiguring one system but the entire production line with minimal breakdowns [19, 20]. Scalability means the possibility to expand overall system capacity such as PLC memory capacity during upgrades and modifications without the need for extra hardware [19, 20]. Reconfigurability means the capability to adapt the highly automated production system rapidly in response to changing market requirements and opportunities with minimal downtime [19, 20].

2.2 Software-defined Automation

The term software-defined was first introduced in the 1970s, as indicated by Barwasser et al.'s [1] article. The applications stated in early research were mainly in the field of electronics, particularly software-defined radio and followed by software-defined networking [1]. Due to recent advancements in technology, there has been an increase in the usage of software-defined approaches in various fields over the past 10 years. This paradigm shift has led to research on the broader concept of software-defined anything (SDx) in different industries to enhance products, processes, and services by means of software [1]. SDx involves decoupling hardware from the system's functionality and enabling its configuration to be managed and controlled only via software [3, 6]. Pang et al. [9] presents SDx as a software-centric paradigm, where the hardware is only for computing and executing. The major functionalities and intelligence are defined through software. By virtualizing physical resources, SDx enables orchestration based on actual demands and actively optimizes hardware utilization [9].

Building upon the principles of SDx, introducing a software-defined approach in industrial automation, the concept of software-defined automation (SDA) has emerged. According to Vettermann and Röper [8], SDA replaces the rigid automation systems (that are common in highly

automated production systems) by introducing flexible and service-oriented architecture where production capabilities are purely controlled using software. Chauvet et al. [11] states that SDA provides reference architecture for designing, managing, and maintaining a highly available, scalable, and flexible automation system. The report published by International Data Corporation defines software-defined automation as “the integration of open-source technologies and standards in industrial processes to control multiple hardware assets from a variety of containerized software running on shared hardware resources” [21].

Consistent with previous research, we define software-defined automation as an emerging paradigm that separates the control logic from dedicated hardware for executing automation tasks in manufacturing, thereby enabling efficient configuration, adaptation and management of automation through software. For instance, PLCs in highly automated production systems are components under the umbrella of SDA in which the PLC software development can be decoupled from the specific hardware. Therefore, the logic software can be developed, updated, and maintained without considering specific hardware PLC. This potentially enables evaluation of innovative software solutions without putting any demands on specific hardware [8, 11, 12, 13].

Although there is limited research on drivers for adopting SDA, few studies have discussed the potential benefits of transitioning to software-defined approaches. According to Vettermann and Röper [8], the driver for implementing SDA is to enhance flexibility and adaptability in production. Ahn et al. [5] and Gaffurini et al. [18] stated that the motivation behind adopting software-defined approaches is to achieve better scalability and reconfigurability in production systems. SDA mitigates hardware dependencies and drives the convergence of IT and OT [8, 18]. As a result, it becomes more convenient for integrating highly automated production systems with IT and introducing advanced technologies like AI [8]. Gaffurini et al. [18] shared that simplified maintenance and updates are the benefits of implementing software-defined approaches in automation. Similar to the process of updating or reconfiguring applications on smart phones without modifying the physical hardware, with SDA the production processes can be adapted and expanded in real time by decoupling hardware and process control [8]. As stated in the research articles [1, 6, 8, 12], software-defined approaches in manufacturing and automation would reduce operational and administration costs.

Previous studies shows that the research on software-defined automation is limited as many studies concentrated on software-defined anything or adjacent topics such as software-defined manufacturing. Within the research on SDA, Vetterman and Röper [8] examined the role of SDA combined with AI for shaping future production, while Pang et al. [9] presented the SDA development framework. However, none of these studies explored about organizational and strategic drivers of SDA adoption together with the challenges of hardware-centric automation. Addressing this gap is critical to assist manufacturing companies realize the potential of SDA to mitigate the challenges of hardware-centric automation.

3. Research Method

The purpose of this study is to examine the challenges of traditional hardware-centric automation and analyze the key drivers for the adoption of software-defined automation in highly automated production systems. Given the exploratory nature of the research, a case study method was selected to be adequate as case studies are considered suitable for studying emerging subjects and underexplored concepts [22] such as SDA. Three large manufacturing companies have participated in this study and they belong to vehicle, machinery, and process equipment

industries. To protect their confidentiality, companies are named fictitiously as Alpha, Beta, and Gamma. To fulfil the research purpose, these companies were selected for this study as they met the selection criteria. The selection criteria includes that they have experience working with highly automated production systems, a clear need for adjustable automation solutions and involves experts working in automation domain and are familiar with the concept of SDA. In this study, the unit of analysis (case) does not refer to the entire company. The case here refers to highly automated, hardware-centric production systems within three large manufacturing companies, focusing on their challenges and potential drivers for transitioning toward software-defined automation (SDA). Alpha's case was selected as the main case for this study based on its active engagement with SDA, including the completion of several pilot implementations. On the other hand, Beta and Gamma are familiar with the concept of SDA but have not yet implemented it in their highly automated production systems. As Beta and Gamma expressed interest in exploring the potential of SDA further, they were invited to participate in a joint workshop together with Alpha. Beta and Gamma's involvement offered complementary insights regarding the challenges of hardware-centric automation and shared how companies without prior SDA experience perceive the potential benefits of SDA purely based on conceptual understanding.

The data collection for this research occurred in two phases. Phase 1 involved a one-week discovery sprint on SDA that took place at company Alpha. The data was collected through handwritten notes during observations and discussions throughout the discovery sprint event. The sprint phase included preparatory meetings, factory visits, one workshop, and final sprint presentation. Together with our research team, 8 experts from Alpha working as automation competence leader, digitalization lead, automation engineer, automation maintenance engineer, software developer, business IT analyst and maintenance technicians participated in this sprint event. During the sprint event, the factory visits to engine assembly, machining, and truck assembly were focused on understanding the challenges of their highly automated production systems, specifically hardware problems connected to PLCs. Following the factory visit, a discussion workshop was carried out with the same set of experts. The workshop was structured around 2 sessions with 3 hours each. During the first session, the experts shared their observations about the factory visits related to the challenges of hardware-centric approaches in automation. The second session was centered around discussing the potential benefits of transitioning towards SDA.

The second phase of data collection involved gathering responses from 5 experts from all three companies participating in a joint workshop held at company Beta's innovation center. The workshop comprised of the structure having SDA concept briefing by our research team for 30 minutes, company-specific group work by experts for 45 minutes and presentations of group work by experts for 20 minutes. The workshop involved 5 experts who were working as automation competence leader, chief project manager in process & IT, team manager in robotics and automation, automation specialist, and future factory manager respectively. The experts were provided with A3 sheets having listed questions that belong to challenges of hardware-centric automation and drivers of software-defined automation. The experts worked together in company-specific groups for about 45 minutes with guidance from the research team. They provided their answers handwritten on sticky notes placed under each question on the A3 sheets. Later in a discussion session with all participants, each company expert presented their responses. During this phase, the data was collected through sticky notes on A3 sheets, and notes were taken during the presentations.

The data collected through handwritten notes on observations and discussions during the weekday sprint event at Alpha were manually typed into a digital document before the analysis. Similarly, the sticky notes responses on A3 sheets collected during the joint workshop were photographed and transcribed into a digital document before interpreting and generating the results. For the data analysis, the research team manually reviewed all the transcribed notes, and responses while grouping them into challenges of hardware-centric automation and drivers of software-defined automation. To ensure validity, the responses that do not correspond to the research purpose were excluded. Besides, the interpreted results were presented back to industry experts to validate the analysis. The empirical findings were compared to the available data in literature to validate the results.

4. Results

4.1 Challenges of Hardware-centric Automation

One of the primary challenges mentioned by company Alpha was the time-intensive nature of scaling, reconfiguring, and verifying its highly automated production systems. The company's reliance on hardware-centric automation solutions, particularly PLCs, limited the system's capacity to adapt to evolving requirements and operational changes. The automation competence leader said – “the existing systems are designed with the focus on technical solutions but not flexible solutions.” The company experts acknowledged that there were situations where they could not adapt to the changing market requirements or customer demands. Additionally, there were issues related to hardware resource utilization. The company used Siemens PLCs in its highly automated production systems. The PLCs were either overpowered or underpowered for certain tasks. For example, the PLC's capacity for Automated Guided Vehicle had reached its capacity limit, and it was not possible to upgrade. On the other hand, PLCs with higher capacity than required were used to control simple tasks such as managing sensor inputs or single function actuators. These imbalances resulted in inefficient resource utilization and higher hardware investment costs, leading to the company's inability to scale and adapt.

Another challenge highlighted by Alpha experts was the vendor lock-in issue. Alpha's highly automated production systems were heavily reliant on certain vendors. Especially, if they wanted to introduce new components or change PLCs or upgrade their existing hardware solutions or even implement alternative software technologies. This resulted in longer delays and higher costs if they had introduced any changes in the current setup to achieve better flexibility and adaptability.

The main challenge stated by Beta was production stoppages in case of executing the changes made to PLCs within highly automated production systems. This made it difficult even to conduct any testing prior to implementation of changes. According to Beta experts, there were also challenges with resource management. They explained that PLC competence within highly automated production systems is limited, and only the maintenance personnel have access to the PLCs, making updates time-consuming. The process & IT chief project manager at Beta has explicitly stated that “it is scaring to do any updates in PLC,” meaning it may take more time to introduce changes and might disrupt production.

The key challenge mentioned by Gamma was vendor lock-in and dependencies on suppliers. The manager and automation specialist at Gamma have discussed about the hardware constraints related to control systems, old age equipment such as old PLCs. For example, the PLCs do not support any of the latest upgrades, making any changes within automation requires additional

technical competence and costs. Furthermore, it was difficult to gain process insights, hindering their transition towards digital transformation.

The challenges of hardware-centric automation presented by each company were combined into three main categories to consolidate similar findings and highlight common challenges among companies. These categories include system rigidity, hardware constraints and vendor lock-in. For example, Alpha's time-intensive scalability, reconfigurability and verification and Beta's production stoppages were combined under challenge Time-intensive & Disruptive Reconfiguration. Similarly, hardware-related issues such as PLC capacity limits, inefficient resource utilization and management and legacy system constraints were grouped under category Hardware Constraints. Table 1 summarizes the findings and indicates which companies reported respective challenge.

Table 1 Challenges of Hardware-centric Automation in Industrial Production Systems

Challenges of Hardware-centric Automation		Company		
		Alpha	Beta	Gamma
System Rigidity	Limited Flexibility & Adaptability	X		
	Time-intensive & Disruptive Reconfiguration	X	X	
	Limited Competence for Updates		X	X
Hardware Constraints	Inefficient Resource Utilization & Management	X	X	
	PLC Capacity & Hardware Limitations for Upgrades	X		X
	Hard to connect Legacy systems for Process insights			X
Vendor	Vendor dependencies for making changes	X		X
Lock-in	Additional costs & delays for making changes	X		X

4.2 Drivers of Software-defined Automation

According to Alpha experts, SDA would enable the convergence of Operational Technology (OT) with Information Technology (IT). In general, OT systems that manage hardware-centric automation operate in isolation to IT, making it challenging to update, maintain and integrate with enterprise systems. The IT/OT convergence would overcome issues of hardware-centric automation, simplifying updates and maintenance of their highly automated production systems. The IT/OT convergence allows the usage of software tools and practices such as DevOps in OT that are prevalent in IT. In addition, they emphasized software-defined nature of SDA would resolve traditional hardware limitations, making it easier for new production system installations, therefore advancing adaptability.

It is highlighted during the workshop that SDA enhances resource utilization not only on the technical side, but also on the human resources aspect. Besides, they discussed about improved efficiency in resource management. SDA would provide a better overview of the resources in highly automated production systems such as PLCs. The automation competence leader at Alpha stated this benefit as "Pay for what we use and use all that we pay for." Enhanced resource utilization would minimize waste and match hardware automation investments directly to the actual operational needs. Besides, SDA would offer better scalability and reconfigurability. The experts believe the capabilities of SDA would assist in scaling the highly automated production

systems using software instead of hardware, thus minimizing the need for buying more hardware PLCs. It is mentioned that SDA would offer the possibility to reuse automation codes and deployment logic. This assists the production personnel to quickly reconfigure and adapt the automation solutions across different production lines or facilities in an efficient way.

Another driver for SDA adoption is its ability to integrate seamlessly with IT, supporting the implementation of advanced technologies like AI. With the existing limitations of traditional hardware-centric automation solutions, it is difficult to implement AI or any other advanced digital technology. Due to the limitations, it may result in Alpha missing out on opportunities and benefits that the latest digital technologies such as AI would bring into production. Experts suggest that SDA may enhance cybersecurity by preventing vulnerabilities tied to specific hardware systems. Overall, Alpha expressed that SDA might reduce costs related to its highly automated production systems, support resilient and flexible production, and promote sustainable development.

Based on their understanding of the concept of SDA, the experts from Beta stated that SDA would reduce costs, offer better control on their systems, and enhance adaptability. Besides, SDA would enable the development of common databases by integrating data across the systems, resulting in simpler access to data and applying AI for improving operational efficiency. The findings from Gamma indicate that SDA would provide benefits for current operations by enabling the development of vendor-agnostic highly automated production systems that are easier to update and controllable via remote. The experts also emphasized that SDA would make it simpler to maintain and update their highly automated production systems. Another driver for adopting SDA is to prevent cyber-attacks and strengthen security within the production systems.

Table 2 Drivers of Software-defined Automation in Industrial Production Systems

Drivers of Software-defined Automation		Company		
		Alpha	Beta	Gamma
System Flexibility & Technological Integration	Enhanced Flexibility & Adaptability	X	X	
	Better Scalability, Reconfigurability & Control	X	X	
	Simplified Updates & Maintainability	X		X
	Vendor Independence & Interoperability	X		X
	IT/OT Convergence & System Integration	X	X	
	Integration of Digital Technologies (AI) & Remote-Control	X	X	X
Operational Efficiency & Cost Reduction	Automation Costs Reduction	X	X	X
	Efficient Resource Utilization	X		X
	Improved Collaboration & Installation Efficiency	X		
Strategic Priorities & Development	Enhanced Cybersecurity	X		X
	Enhanced Sustainability	X		

The drivers of software-defined automation presented by each company were combined into three main categories to consolidate similar findings and highlight common drivers among companies. These categories include system flexibility and technological integration, operational efficiency and cost reduction and strategic priorities and development. Table 2 summarizes the findings and indicates which companies presented each driver.

5. Analysis and Discussion

5.1 Challenges of Hardware-centric Automation

The companies identified system rigidity as a major challenge. Alpha and Beta reported the challenge time intensive & disruptive reconfiguration. Alpha highlighted related challenges like limited flexibility and adaptability, along with time-intensive scaling, reconfiguring, and verifying its highly automated production systems, while Beta stressed about production stoppages during PLC updates. These system rigidity challenges relate with the theoretical understanding of challenges of hardware-centric approaches discussed by Ahn et al. [5] and others [3, 12, 13]. Ahn et al. [5] emphasized that tight coupling of hardware and software restricted the ability of highly automated production systems to be flexible and adaptable. Similarly, Lechler and Verl [3] presented that the coupling of hardware and software results in longer lead times during reconfiguration. This study extends current understanding by showing that rigidity in highly automated production systems is not only a technical or operational issue but also organizational. For instance, Beta and Gamma mentioned the challenge of limited competence for making updates within highly automated production systems. Beta reported issues such as only maintenance people have access to PLCs. These organizational aspects of rigidity regarding competence working with hardware-centric automation are rarely discussed in previous literature.

Hardware constraints were another challenge category that includes challenges such as inefficient resource utilization and management, PLC capacity and hardware limitations for upgrades and hard to connect legacy systems for process insights. Alpha stated some PLCs were being overpowered for simple tasks and some reaching their capacity limits affecting upgrades and scalability. Gamma elaborated that the old legacy equipment and PLCs could not support the latest upgrades due to hardware constraints. Based on the previous research studies [14, 15, 18], it is understandable that limited memory capacities and vendor-specific hardware prevent upgrades affecting scalability. However, this study adds nuance by identifying inefficient resource utilization and management as a challenge that is less emphasized in literature. One challenge that is not explicitly stated in literature but pointed out by Gamma is the inability to connect with their legacy systems due to hardware constraints. As a result, it became challenging to gain process insights and visibility, hindering their transition towards digitalization. This research provides empirical evidence on hardware constraints causing operational delays, inefficient resource utilization and impacting digitalization in highly automated production systems in large manufacturing companies. These empirical findings reinforce the argument supporting the need for decoupling hardware and software discussed in previous studies [3, 4, 6, 8].

Another pressing issue with hardware-centric automation is the vendor lock-in. Companies Alpha and Gamma shared introducing any changes like new components or upgrading systems would require additional costs and time due to vendor dependencies. This relates to the vendor lock-in challenge described by Bibl et al. [14] and limited interoperability noted by Balakrishna et al. [17]. Our findings add details by showing how vendor dependencies obstruct innovation and slow responsiveness to market changes, thereby hindering long-term growth in manufacturing industry.

5.2 Drivers of Software-defined Automation

The prime driver for SDA adoption according to the companies is system flexibility and technological integration. Alpha and Beta highlighted the drivers such as enhanced flexibility and adaptability, better scalability, reconfigurability and control, IT/OT convergence and system integration. Alpha and Beta discussed about the importance of integration possibilities of advanced digital technologies (AI), while Gamma expressed about remote control possibilities. Alpha and Gamma mentioned simplified updates, maintainability, vendor independence and interoperability as the drivers of SDA. These drivers confirm prior research on the potential of software-defined approaches in enhancing flexibility [8], adaptability [8], and reconfigurability [5]. Gaffurini et al. [18] emphasized on benefits such as scalability, simplified updates and maintainability. According to Vettermann and Röper [8], SDA would drive IT/OT convergence and enable the integration of advanced digital technologies such as AI. This study reinforces these drivers of SDA by providing empirical evidence from the companies. This research introduces vendor independence and interoperability and remote-control possibilities as new drivers that is not explicitly discussed in earlier literature. Our study reinforces these drivers and confirms that SDA continues to be viewed as a key enabler for highly automated production systems supporting their ability to continuously adapt to changing demands.

Alpha emphasized strategic priorities and development as one of the drivers of SDA. This includes drivers such as enhanced cybersecurity and sustainability. Sarker et al. [15] pointed out cybersecurity challenges in hardware in automation, which closely relates to Alpha's motivation behind SDA adoption is to strengthen cybersecurity. Regarding sustainability, Alpha stressed that SDA would minimize waste by managing resources efficiently to fast-changing market demands and requirements. While the previous research studies [5, 8, 18] concentrated more on technical and operational benefits, this study expands the scope by revealing enhanced cybersecurity and sustainability as emerging drivers for implementing SDA. This suggests a shift in SDA research towards addressing broader strategic priorities and imperatives as well, aligning automated production development with corporate responsibility and risk management.

The study presents operational efficiency and cost reduction as the central drivers for SDA adoption. Based on the empirical findings from Alpha, this study points out that SDA is likely to foster system integrations and improve collaborations across traditionally siloed domains. The IT/OT convergence that is possible with SDA facilitates reusability of automation code and deployments. Moreover, it promotes DevOps inspired methodology in OT for automating deployments, testing, and updates of automation programs in PLCs. Consequently, new production systems installation would become simpler and more efficient. Alpha and Gamma believe SDA has the potential to improve resource utilization. The drivers improved collaboration and installation efficiency, and efficient resource utilization are less emphasized in prior research. All case companies shared that SDA would minimize automation related costs which aligns with the study published by Vettermann and Röper [8]. These drivers indicate a growing recognition of SDA's role in bridging traditional silos and facilitating smoother deployment and cross-functional teamwork. Additionally, they confirm that SDA remains as a promising approach for optimizing production economics and resource management.

Despite these benefits, SDA adoption remains limited, primarily due to concerns about reliability, safety, and transition costs. This tension between recognized advantages and adoption barriers highlights how this study adds new perspectives by uncovering dimensions that are often overlooked such as organizational and strategic factors influencing automation decisions in large manufacturing companies.

6. Conclusion

The purpose of this study was to examine the challenges of traditional hardware-centric automation and analyze the key drivers for the adoption of software-defined automation in highly automated production systems. Using a case study method, the research purpose was fulfilled by examining challenges such as system rigidity, hardware constraints, and vendor lock-in that limit flexibility, adaptability and scalability in traditional hardware-centric automation. The study analyzed the key drivers for transitioning towards software-defined automation which include system flexibility and technological integration, operational efficiency and cost reduction, and enhanced sustainability and cybersecurity. This study contributes to the literature by providing empirical evidence and introducing new drivers such as vendor independence and interoperability, efficient resource utilization, and improved collaboration and installation efficiency that are not extensively discussed in previous research. The findings suggest SDA adoption would boost resource efficiency by overcoming hardware constraints and dependencies, thus promoting sustainable development. The research reveals that the drivers enhanced cybersecurity and sustainability indicate SDA adoption is motivated by not just operational efficiency but also broader corporate priorities. One key takeaway from this study is that SDA adoption reflects a fundamental change in the design and development of highly automated production systems. The transition from hardware-centric to software-defined automation would require reassessment of traditional production automation strategies to enhance flexibility, adaptability, scalability and enable easier integration of advanced digital technologies. Despite the valuable findings, there are some limitations to consider. The study sample was limited to few experts from three large manufacturing companies. To improve the generalizability of the findings, further studies should gather insights from a broad range of experts from varied manufacturing sectors and company sizes. Future research should examine how SDA transforms the design and development of production systems and its potential impacts on operations. Besides, further studies should explore organizational capabilities and develop implementation frameworks that accelerate the adoption of SDA in manufacturing companies.

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