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Integrating Cyber-Physical Systems in Manufacturing: Challenges and Future Directions

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Abstract

The integration of Cyber-Physical Systems (CPS) has become a central driver of Industry 4.0 in modern manufacturing, enabling smarter automation, real-time data sharing, and improved operational performance. However, despite these advantages, the adoption of CPS is still limited by a range of technological and organizational challenges. This study explores CPS integration in manufacturing through a qualitative, literature-based analysis, with a focus on key challenges, emerging opportunities, and future directions. Drawing on a thematic review of existing research, the study identifies three main areas of concern. These include technological challenges such as interoperability issues and cybersecurity risks, organisational barriers like skills shortages and resistance to change, and emerging opportunities linked to technologies such as digital twins and predictive analytics. The findings reveal that these factors are highly interconnected, suggesting that successful CPS adoption depends on aligning technological systems with workforce capabilities and broader organisational strategies. This study contributes to the field by offering a clear and structured synthesis of the challenges associated with CPS integration, while also highlighting practical considerations for implementation. It emphasises the importance of standardisation, continuous workforce development, and strong cybersecurity measures to support the development of sustainable, CPS-enabled manufacturing systems.

Keywords
Cyber-physical systems, Manufacturing, Industry 4.0, Cybersecurity, Systems.

1. Introduction
The rapid development of Industry 4.0 has brought significant changes to manufacturing, with Cyber-Physical Systems (CPS) emerging as a central driver of this transformation. By combining computational technologies with physical processes, CPS enables real-time monitoring, intelligent automation, and more informed decision-making. This integration allows manufacturing systems to operate with greater efficiency, flexibility, and sustainability.

The integration of Cyber-Physical Systems into manufacturing is fundamentally reshaping the sector, bringing both significant improvements in adaptability and a range of technical, organisational, and workforce-related challenges (Sinha and Roy 2020). CPS enables the development of smart factories characterised by self-organising, flexible, and data-driven production processes. However, despite these advantages, issues such as system interoperability, data security risks, workforce skill gaps, and the complexity of scaling these systems continue to present barriers that require carefully considered solutions (Sayem et al.2022). In practice, CPS enables machines, systems, and processes to communicate and collaborate with minimal human intervention. Through the use of advanced sensors, actuators, and data analytics, production processes can be continuously monitored and optimised. This leads to higher productivity, reduced operational costs, and improved product quality.

More broadly, CPS serves as a bridge between manufacturing and information technology, playing a key role in enabling Industry 4.0 and accelerating digital transformation on the factory floor (Sinha and Roy 2020). Existing literature highlights a range of enabling technologies, including the Internet of Things (IoT), digital twins, cloud computing, and machine learning. These technologies are central to the development of smart manufacturing environments, where seamless integration across both horizontal and vertical system layers is essential. Achieving this level of integration requires not only robust technical architectures but also alignment with rapidly evolving market and production demands (Jiang 2018).

While there is a growing body of research on CPS in manufacturing, much of it remains fragmented and largely descriptive. There is therefore a clear need for a more structured synthesis that brings together the key challenges, opportunities, and future research directions in a coherent manner. This study addresses this gap by answering the following research question: What are the key challenges, opportunities, and future directions of CPS integration in manufacturing?

The objectives of this study are to identify the key challenges associated with the integration of CPS in manufacturing, to analyze emerging technologies and opportunities that support CPS-enabled transformation, and to synthesize existing knowledge into structured insights that can inform the development and improvement of modern manufacturing systems.

2. Literature Review

CPS integration has become a disruptive method that has the potential to completely change industrial operations. Real-time data sharing and decision-making are made possible by the convergence of intelligent software systems and physical equipment, which is driving this evolution (Monostori et al. 2016). According to Lee et al. (2008), the use of CPS has led to a considerable improvement in manufacturing efficiency and sustainability by enabling intelligent factory automation and real-time data analytics. This integration enhances manufacturing performance by improving efficiency, flexibility, and responsiveness.

By integrating networked systems, actuators, and sensors into actual machinery, CPS may be integrated into the production environment to continually gather and analyze data. By enabling dynamic modifications and optimization, this integration promotes a more responsive and flexible production process (Rajkumar et al. 2010). Predictive maintenance, which can anticipate equipment breakdowns and minimize downtime, is made possible by the real-time capabilities of CPS. This boosts overall production (Jazdi 2014). Furthermore, product development and lifecycle management have been completely transformed by the idea of "digital twins," which uses virtual representations of physical assets for analysis and simulation (Tao et al. 2018).

Notwithstanding the encouraging future of CPS, a number of obstacles prevent its smooth incorporation into production. Because there are so many different types of devices and systems that need to work together and communicate, interoperability problems can occur (Sung 2018). Another major worry is cybersecurity since more connections expose production systems to possible cyberattacks (Wan et al. 2016). Furthermore, a major obstacle is workforce readiness, as there is an urgent demand for qualified workers who can oversee and use cutting-edge CPSS technologies (Rosen et al. 2015).

Promising developments in CPS could lead to more automation, sustainability, and optimization in the industrial sector. According to Brous et al. (2020), real-time data analytics will be essential for predictive maintenance and for customizing manufacturing processes to satisfy particular market demands. By offering precise and useful insights, the ongoing development of digital twins will improve operational efficiency and product development even more (Kritzinger et al., 2018).

Industry stakeholders and academics must work together to address the obstacles to CPS integration and realize its full potential. Collaboration can result in the creation of training programs to equip the workforce for upcoming needs as well as standardized procedures and improved cybersecurity measures (Lee et al. 2008). Adopting CPS boosts competitiveness and creates the foundation for a manufacturing ecosystem that is more robust and sustainable (Xu et al., 2018). Ignoring this important area of research could have serious consequences for the manufacturing sector and beyond.

Manufacturing businesses run the danger of lagging behind global competitors that are embracing and developing CPS technologies at a quick pace if research into the technology is not continued. Investments in CPS by nations and businesses have a positive impact on innovation, flexibility, and productivity. German Industry 4.0 efforts, for example, show how CPS may improve production processes and produce better goods and services (Kagermann et al. 2013). Manufacturers who disregard CPS research, on the other hand, can find it difficult to stay up with technological developments and risk losing market share to rivals who are more advanced in this area.

With the help of CPS, industrial processes can be monitored and optimized in real time, greatly increasing productivity and cutting costs. Manufacturers lose out on possibilities to optimize their processes when they don't conduct research and development in CPS, which increases waste and inefficiencies. As per Jazdi (2014), predictive maintenance, enabled by CPS, has the potential to avert expensive downtime and prolong the life of machines. Insufficient investigation may result in an ongoing dependence on reactive maintenance approaches, which could cause frequent malfunctions and elevated cost for repairs.

Manufacturing is a significant source of pollution in the environment, and CPS provides viable ways to improve sustainability. With intelligent automation and real-time data analytics, CPS can decrease waste, optimize resource utilization, and lower energy consumption (Broy et al. 2012). Ignoring this research would impede the development of environmentally friendly industrial techniques. As a result, industries that do not achieve environmental standards and sustainability goals may see increased governmental pressure and social backlash.

The manufacturing workforce must adjust to new responsibilities and skills as CPS technologies develop. According to Rosen et al. (2020), research on CPS emphasizes the human element, training and preparing people for the future and technological developments. There will be a major gap in workforce preparation without focused research initiatives, which will result in a shortage of qualified workers able to run and maintain complex industrial systems. This lack of expertise may limit the industry's overall growth potential and hinder the adoption of CPSS technologies.

By examining novel applications and enhancing current technology, CPS research stimulates innovation. According to Monostori et al. (2016), ongoing innovation is crucial for the advancement of manufacturing techniques and the creation of new goods. Ignoring CPS research could lead to a stagnation of creative concepts and technology, making it more difficult for the sector to adapt to new possibilities and problems. A region's total technical advancement and economic growth may be impacted by this stagnation, in addition to the manufacturing sector.

3. Methods

This study adopts a qualitative literature-based research approach to analyze the integration of Cyber-Physical Systems (CPS) in manufacturing. The methodology focuses on synthesizing secondary data from existing academic and industry sources to identify key themes and insights. A qualitative approach was selected to enable an in-depth exploration of CPS integration challenges and opportunities. This approach allows for the interpretation and synthesis of existing knowledge in a structured manner. Relevant literature was collected from peer-reviewed journals, conference proceedings, and industry reports. The selection focused on studies related to CPS, Industry 4.0, smart manufacturing, and digital technologies. A thematic analysis approach was used to identify recurring patterns and key themes within literature. The data was categorized into three main areas: technological challenges, organizational barriers, and emerging opportunities.

The study is informed by Network Society Theory (Castells, 2010), which emphasizes the role of interconnected systems and information flows. This perspective supports the analysis of CPS as a network-driven transformation of traditional manufacturing systems.

4. Results and Discussion

4.1 Results

This chapter outlines the findings from a thematic analysis of the challenges associated with implementing Cyber-Physical Systems (CPS) in manufacturing environments. It is based on insights gathered from the reviewed literature, which reveal recurring patterns affecting how CPS is adopted, integrated, and performs in practice. The findings are organized into key themes that reflect both the technical difficulties and organizational constraints influencing CPS implementation. To improve clarity, these themes are grouped into technological and organizational challenges, showing the two main categories of barriers that emerge in CPS-driven transformation.

4.1.1 Overview of Thematic analysis

The thematic analysis identified five key themes that capture the main challenges experienced in CPS environments. Together, these themes highlight the complexity of CPS adoption, requiring both strong technological systems and a well-prepared organization. The key themes are; Interoperability and integration of heterogeneous systems, Data security and cyber threats, Human factors and skills gaps, Transformation strategy and organizational support and Data management and real-time analytics. To make the findings easier to interpret, these themes are further grouped into two broader categories:

- Technological challenges, which relate to system design, infrastructure, and data processing and management, and
- Organizational challenges, which focus on people, skills, leadership, and how well the organization supports and aligns with CPS adoption.

Table 1 provides a comprehensive summary of the themes, their associated key issues, descriptions, and implications.

Table 1. CPS Integration Challenges in Manufacturing

Theme	Key Issues	Description	Key Implications
Interoperability and Integration of Heterogeneous Systems	Legacy system incompatibility; lack of standardization; fragmented architectures	CPS environments require integration of diverse legacy and modern systems, creating significant interoperability challenges that affect real-time communication, data exchange, and system upgradeability (Zakoldaev et al. 2019; McCormick et al. 2020).	Limits seamless data flow and system coordination; slows digital transformation; necessitates modular architecture and standardization efforts (Zakoldaev et al. 2019; McCormick et al. 2020).
Data Security and Cyber Threats	Increased cyber vulnerability; inadequate security tools; operational risk exposure	Increased connectivity in CPS-enabled factories expands the attack surface, making manufacturing systems vulnerable to cyberattacks, data breaches, and operational disruptions (Lee et al. 2019).	Heightened risk to operational continuity and data integrity; requires security-by-design approaches and specialized industrial cybersecurity frameworks (Lee et al. 2019).
Human Factors and Skills Gap	Digital skills shortages; resistance to change; limited trust in automation	Successful CPS integration depends on workforce readiness, including digital literacy, adaptability, and trust between human operators and automated systems (Dabic-Miletic 2023).	Slows adoption of CPS technologies; increases implementation resistance; requires continuous training and cognitive human–machine collaboration frameworks (Dabic-Miletic 2023).
Transformation Strategy and Organizational Support	Weak digital strategies; misalignment of business and technology goals; limited leadership commitment	Many organizations lack coherent and aligned digital transformation strategies, resulting in fragmented CPS adoption efforts (Wikström and Gedda 2022).	Reduces long-term sustainability of CPS initiatives; necessitates strong leadership, strategic alignment, and inclusive planning structures (Wikström and Gedda 2022).

Data Management and Real-Time Analytics	High data volumes; insufficient processing infrastructure; limited real-time analytics capability	CPS generates large-scale real-time data streams requiring advanced systems for collection, storage, processing, and analysis (Lee et al. 2019; Monostori et al.2016).	Creates pressure on IT infrastructure; demands scalable analytics, edge computing, and robust data governance frameworks (Lee et al. 2018; Monostori et al.2016).

The themes presented in Table 1 provide a structured overview of the key CPS challenges. These themes are further explored in the sections below, beginning with technological challenges followed by organizational considerations.

4.1.2 Technological challenges

Technological challenges represent structural and system-level barriers that hinder the effective implementation and operation of CPS. These challenges are primarily associated with system integration, cybersecurity, and data management capabilities. The first category of findings focuses on technological challenges, which form the foundation of CPS implementation and directly affect system functionality and integration.

- Interoperability and Integration of Heterogeneous Systems

One of the most prominent challenges identified is the difficulty of integrating heterogeneous systems within CPS environments. Manufacturing ecosystems often consist of a combination of legacy systems and modern digital technologies, which lack standardized communication protocols (Monostori et al. 2016). This results in fragmented system architectures that hinder interoperability. The findings indicate that such incompatibility negatively affect real-time data exchange and system coordination. Consequently, organizations are required to adopt modular architecture and invest in standardization efforts to ensure seamless integration and improved system scalability (Trappey et al. 2016).

- Data Security and Cyber Threats

The increased interconnectivity inherent in CPS significantly expands the cyberattack surface of manufacturing systems. As such, cybersecurity emerges as a critical concern in CPS implementation. The findings show that many organizations face heightened exposure to cyber threats, including data breaches and operational disruptions (Keerthi et al. 2017). This underlines the need for robust cybersecurity strategies, including security-by-design principles and the adoption of specialized industrial cybersecurity frameworks to safeguard system integrity and ensure operational continuity.

- Data Management and Real-Time Analytics

CPS environments generate vast volumes of data in real time, placing considerable demands on existing IT infrastructure. The findings reveal that many organizations lack adequate data processing capabilities to effectively manage and analyze these data streams (Cui 2021). This limitation restricts the ability to derive actionable insights and optimized decision-making. To address this, organizations must invest in scalable data analytics solutions, such as edge computing and advanced data governance frameworks, to support efficient data utilization.

In addition to technological barriers, organizational challenges play a critical role in determining the success of CPS adoption.

4.1.3 Organizational Challenges

Organizational challenges reflect the human, strategic, and managerial dimensions of CPS implementation. These factors are critical in determining whether technological advancements can be successfully adopted and sustained.

- Human Factors and Skills Gap

The findings highlight that workforce readiness plays a central role in CPS adoption. A lack of digital skills, combined with resistance to change and limited trust in automation, significantly impedes the implementation process (Wikström and Gedda 2022). These skills gaps not only slow adoption but also increase the likelihood of implementation failure. Addressing this challenge requires continuous workforce training, upskilling initiatives, and the development of collaborative human-machine interaction frameworks.

- Transformation Strategy and Organizational Support

Another key challenge identified is the absence of coherent digital transformation strategies. Many organizations struggle with aligning business objectives with technological initiatives, resulting in fragmented CPS adoption efforts (Wikström and Gedda 2022). The findings emphasize that strong leadership commitment and strategic alignment are essential for the long-term sustainability of CPS initiatives. Organizations must adopt holistic and inclusive planning approaches to ensure that CPS implementation aligns with broader organizational goals.

4.1.4 Results Summary

The results of this study show that integrating Cyber-Physical Systems (CPS) in manufacturing is influenced by a mix of technological and organizational challenges. On the technical side, issues like limited interoperability, cybersecurity risks, and difficulties in managing large volumes of data can directly affect how well these systems perform and how easily they can scale. At the same time, organizational factors such as skills shortages and a lack of clear strategic direction play a major role in determining whether CPS implementation succeeds in the long term.

These findings make it clear that adopting CPS is not just a technical upgrade. It requires organizations to align advanced technologies with the right skills, strategies, and support structures. Overall, the results provide a clearer picture of the barriers to CPS integration and lay the groundwork for exploring practical ways to address them.

4.2 Discussion

The findings show that technological barriers continue to limit the effective implementation of CPS in manufacturing. A major issue is the lack of interoperability between different systems. Many organizations still rely on a mix of legacy equipment and newer digital technologies, which often do not communicate well with each other. This creates fragmented system architectures and makes seamless integration difficult (Monostori et al., 2016). This ongoing interoperability problem suggests that many companies have not yet moved toward fully standardized or modular system designs. From the perspective of Network Society Theory (Castells, 2010), the success of interconnected systems depends on how efficiently information flows between them. In CPS environments, poor integration disrupts these flows and reduces overall system performance. CPS integration in manufacturing reflects a transition toward a networked production environment, where machines, systems, and human actors are interconnected through real-time data exchange.

4.2.1Technological Challenges

The technological challenges identified, especially those related to interoperability, point to deeper issues in how effectively manufacturing systems are connected. From the perspective of Network Society Theory, the true value of a system lies in how well it enables smooth communication and continuous information flow between its different parts (Castells, 2010). In practice, however, the findings show that many manufacturing environments are still dealing with a mix of incompatible systems and a lack of standardisation. This creates fragmented networks where information cannot flow freely. As a result, CPS struggles to deliver its full potential, particularly when it comes to real-time coordination and seamless integration (Monostori et al., 2016). Challenges around data management and real-time analytics further highlight these gaps. Ideally, in a well-functioning network, data should move quickly and efficiently to support timely decision-making. The fact that many organisations are unable to fully use their real-time data suggests that they have not yet reached the level of network maturity described by Castells (2010).

Cybersecurity adds another layer to this issue. While increased connectivity is a key strength of networked systems, it also introduces new risks. The findings show that as systems become more interconnected, they also become more exposed to cyber threats, making security a critical concern in CPS environments (Lee et al., 2020). This reinforces the need for secure and resilient network infrastructures to ensure that CPS-enabled manufacturing systems can operate safely and reliably.

4.2.2 Organizational Challenges

From an organizational point of view, the findings show that human and strategic factors play a major role in how well networked systems perform. Network Society Theory does not focus only on technology and connectivity, but also highlights the importance of people, social structures, and institutional coordination within these networks.

The skills gap identified in the study reflects a mismatch between technological progress and human capability. In a networked environment, employees are expected to actively engage with digital systems and contribute to interconnected processes. However, limited digital skills and resistance to change weaken this human element, which in turn reduces the overall effectiveness of the system. In the same way, the lack of clear transformation strategies and strong leadership support points to weak organizational alignment. Castells (2010) argues that effective network systems depend on coordination and shared goals across all parts of the network. When this alignment is missing, it becomes difficult to maintain coherence, which often results in fragmented and inconsistent CPS implementation efforts.

4.2.3 Future Directions for CPS Integration in Manufacturing

Recent developments point to several promising directions for improving how CPS is implemented and used in manufacturing. One important shift is the move from traditional models like the 5C architecture or ISA-95 toward more expanded frameworks, such as the 8C architecture. By adding elements like coalition, customer, and content, these newer models provide a more complete view of how CPS should be integrated within smart factories. They move beyond purely technical layers and begin to incorporate collaboration, user needs, and information flow in a more holistic way. Another emerging area is the combination of digital twins with immersive technologies and the industrial metaverse. This integration is opening up new possibilities for real-time system monitoring, virtual training environments, and even remote operation of manufacturing processes. Instead of only analyzing systems after the fact, organizations can now simulate, test, and optimize operations in dynamic virtual spaces.

Big data and artificial intelligence are also becoming central to CPS environments. These technologies make it possible to analyze large volumes of data in real time, supporting applications such as predictive maintenance, process optimization, and smarter resource allocation. As a result, manufacturers can operate more efficiently while also becoming more flexible in responding to changes. In addition, there is a growing focus on self-adaptive and autonomous systems. These are CPS that can learn from data, make decisions on their own, and adjust processes without constant human intervention. This is particularly valuable in modern manufacturing, where there is increasing demand for customized products, smaller production batches, and rapid responses to market shifts.

From an organizational perspective, there is a clear need for continuous workforce development. Training programmes should focus on improving digital literacy, technical skills, and the ability to collaborate with automated systems.
organizations must also invest in change management strategies to reduce resistance and build trust in CPS technologies. This includes promoting a culture of innovation and encouraging employee involvement in the transformation process. Furthermore, strong leadership and strategic alignment will be essential. Organizations should develop clear digital transformation strategies that align technological investments with long-term business objectives.

5. Conclusion

The aim of this study was to examine the integration of Cyber-Physical Systems (CPS) in manufacturing, with a focus on identifying key challenges, exploring opportunities, and highlighting future directions. A qualitative, literature-based approach was adopted, and thematic analysis was used to synthesize existing research and uncover recurring patterns in CPS implementation. The findings were grouped into two main categories: technological challenges and organizational challenges. Technological challenges included interoperability issues, cybersecurity risks, and limitations in data management and real-time analytics. Organizational challenges, on the other hand, were mainly linked to skills gaps, resistance to change, and weak strategic alignment.

In conclusion, Cyber-Physical Systems represent a significant shift in modern manufacturing, driving a move toward more intelligent, connected, and data-driven production environments. However, as this study shows, integrating CPS is not simply a technical upgrade, it is a complex and layered process shaped by both technological capabilities and organizational realities. Although CPS reflects the principles of a networked society, its successful implementation depends on how well organizations can achieve seamless system integration, ensure internal alignment, and develop a workforce ready for digital transformation. Those that manage to balance these elements effectively will be better positioned to unlock the full potential of CPS and remain competitive in the rapidly evolving Industry 4.0 landscape.
In conclusion, Cyber-Physical Systems stand as a powerful shift in modern manufacturing, marking a move toward more intelligent, connected, and data-driven production environments. Yet, as this study shows, integrating CPS is not a straightforward technical upgrade, it is a layered and complex process shaped by both technological capabilities and organizational realities. Although CPS reflects the ideals of a networked society, its success ultimately depends on how well organizations can bring together seamless system integration, internal alignment, and a workforce that is

prepared for digital transformation. Those that manage to balance these elements effectively will be in a stronger position to unlock the full value of CPS and stay competitive in the rapidly evolving Industry 4.0 landscape.

Recommendations

Based on the findings, the following recommendations are proposed:

Technological Recommendations

- organizations should adopt standardized communication protocols to improve interoperability between systems.
- Investment in advanced cybersecurity frameworks is essential to protect interconnected manufacturing systems.
- Companies should implement scalable data infrastructure, including cloud and edge computing, to manage real-time data effectively.

Organizational Recommendations

- Continuous workforce training and upskilling programmes should be prioritized to address digital skill gaps.
- Organizations should develop strong management strategies to reduce resistance to new technologies.
- Leadership must ensure strategic alignment between technological initiatives and business objectives.

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