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Coordination in cyber-physical production systems: Challenges and perspectives

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Abstract

Introduction: The evolution of Industry 4.0 production systems enables the delegation of part of human intelligence to machines, which facilitates the design and management of these intelligent production systems, known as cyber-physical systems (CPS), and enhances their performance. Artificial Intelligence (AI) plays a crucial role by providing a learning capability based on the analysis of massive data generated by the physical entities of production systems. This allows not only for understanding the system's behavior but also for increasing real-time responsiveness in case of disturbances.

Objectives: The objective of this paper is to map the challenges associated with coordination in intelligent production systems, enabling organizations to better understand, analyze, and address risks and opportunities effectively. The paper focuses on highlighting key issues related to the coordination of physical and cyber entities in Industry 4.0 production systems.

Methods: The study is centered on the analysis of cyber-physical systems by identifying three main aspects:

1. The context in which the production systems operate,
2. The configuration of intelligent production systems,
3. The coordination constraints that require human intervention.

The methodology includes a literature review and a comparative analysis of existing approaches to CPS coordination.

Results: The findings indicate that effective coordination of intelligent production systems in Industry 4.0 depends heavily on an organization’s ability to configure and adapt these systems based on operational constraints and the need for human intervention. The risks and opportunities related to CPS coordination are better identified, which facilitates their management by organizations.

Conclusions: This paper provides a mapping of the coordination challenges in intelligent production systems, offering insights for improving performance while minimizing risks. Organizations can now approach these challenges more effectively by optimizing the collaboration between physical and cyber entities.

Keywords: coordination, intelligent production systems, CPPS, challenges and perspectives

Introduction

The advanced technologies that have emerged in the context of Industry 4.0 (I4.0), such as cyber-physical systems (CPS), the Internet of Things (IoT), artificial intelligence, and big data, promote the connection and collaboration between humans, products, industrial equipment, data, intelligent analysis, decision and execution systems [1], [2], [3], forming a new type of production system, intelligent, including a real and a virtual environment [4], [5]. I4.0 is a paradigm that transcribes the insertion of new technologies in the industrial world [6]. Many studies are currently conducted on technology groups such as IoT [7], massive data processing [8], smart factory performance [9], the emergence of a new approach to steering production processes [10], proposal of new services and new smart products . Smart production systems are highly digitized and networked systems [11]. It relies on intelligent processes to create fully self-organizing and optimized production facilities [12]. The processes are executed with minimal human interaction, relying on advanced technologies [13]. In their work [14], [15], [16], the authors state that the characteristics of a smart production system are real-time capability, virtualization, interoperability, decentralization, service orientation, and modularity. An intelligent production system therefore links physical and virtual environments via a CPS. The result is a fusion of two completely different but complementary environments, building a cyber-physical production system.

Cyber-physical production systems (CPPSs) are recognized as one of the leading technologies for designing and building intelligent and responsive production systems [4]. They are considered a promising I4.0 technology that will improve manufacturing operations from the perspectives of productivity, efficiency, responsiveness, and adaptability.

Indeed, a CPPS consists of a set of computing devices communicating with each other and interacting with the physical world, which represents the production floor, through sensors and actuators in a feedback loop [17]. In these systems, there are implicit feedback connections where the computer and network devices directly affect the physical system [18]. Traditionally, the coordination of industrial production systems has been achieved using dedicated electronic systems with analog process variables and control signals communicated through twisted pair cables [19]. As automation functions evolve, so do communication architectures. With the advent of the Internet and cloud computing, the Internet Protocol has been used for more advanced data collection and control applications [20]. In the current context, CPPSs are expected to bring huge benefits in terms of efficiency, reliability, and productivity in industrial systems. The advent of CPPSs offers new ways to compete with the evolving and unpredictable demands of the market. However, due to transformation barriers, the implementation of CPPSs in industrial practice is still in its infancy [21]. In fact, when a CPPS is implemented in a plant, old systems are not easily replaced by new ones, as they are expensive to acquire and operate [22]. Therefore, CPPS adaptation is not yet triggered for most industrial organizations, which provides an opportunity for researchers to propose models and new architectures to facilitate CPPS operation.

CPPSs are systems that can learn and adapt to their environment using artificial intelligence and machine learning technologies. However, coordination in CPPSs can present several challenges, as it involves managing the interactions between different system components and their relationship with the environment [23]. In the literature, there are few articles that bring together all the problems related to CPPSs, especially their coordination. The objective of the article is to propose a mapping of the issues related to coordination in cyber-physical production systems, with the aim of allowing researchers and organizations to have a tool that aggregates the challenges to better understand and analyze them to address them in an optimal way. This paper presents a nonexhaustive list of current challenges related to coordination in CPPSs based on the scientific literature and the most recent research.

This paper is organized as follows: Section 2 presents a systemic approach to the smart production system and the possible interactions with its different elements. Section 3 discusses the challenges and issues related to the coordination of smart production systems based on the literature and following the decomposition performed in the systems approach. Finally, Section 4 states preliminary conclusions and future work that will follow this research.

1. Intelligent production systems: systemic approach

Intelligent systems are developed to accomplish a specific task with minimal human interaction (Bagheri et al., 2015a). To do this, these systems must be able to adapt and self-run in any given environment (Knud Lasse, 2015; Stancel et al., 2017).

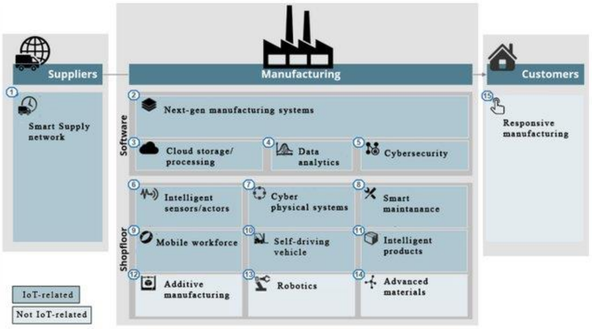

Figure 1: The key elements of SPI [24]

A cyber-physical production system (CPPS) consists of a physical level, another cyber level, and a digital coordination interface. The physical system can communicate and work with the cyber system without or with human mediation through a digital coordination interface, which is considered a system of virtual objects that represent automatic processes in production execution (planning, scheduling, etc.)[25]. The physical system refers to objects, called physical entities, such as operators, machines, products, activities, or the environment, that need to be monitored and controlled in the real world. The communication between the physical and cyber levels takes place via sensors and actuators. The sensors collect real-time data from the physical world and automatically transmit it to the cyber system, while the actuators act on the physical world based on the cyber system's outputs. The cyber element of CPS provides real-time functions such as task analysis and scheduling, data processing and storage, and decision making. At the cyber level, there are virtual objects, considered a digital twin, which is a virtual model designed to mirror a physical object [26]

A systemic approach is proposed to properly identify the challenges related to the topic of coordination in CPPSs based on the work of [27]. As shown in ***Figure 2***, we decompose the system into three parts: the first part is about the environment in which production systems evolved, then the role of the human in steering, and finally the intelligent production system itself and the set of transformation elements associated with the characteristic "Intelligent".

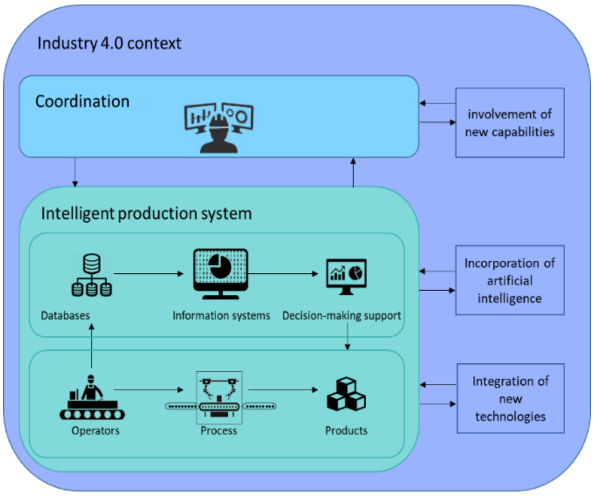

Figure 2: Intelligent production system

2.1 Interaction between "The Industry 4.0 Context" and "Coordination:

The context of Industry 4.0 offers the opportunity to use data and technology to create and coordinate intelligent production systems [28]. One of the main benefits of Industry 4.0 is the ability to coordinate production processes using data and automation. This can result in optimized control by coordinators or supervisors, as well as better communication between machines, which can minimize errors and improve product quality [18]. In addition, Industry 4.0 can also provide the opportunity to implement predictive maintenance, which can help reduce downtime and improve operational efficiency (Cardin 2015). Finally, the use of advanced analytics and machine learning algorithms can help identify potential problems and provide the solutions needed to resolve them [29].

While the I4.0 environment has the potential to revolutionize the way production systems are coordinated, it also has the potential to have a negative impact. One of the main problems with Industry 4.0 is that it requires a high level of communication between different system components [30]). However, due to the complexity of the systems involved, it can be difficult to ensure that all components work in sync. This can lead to delays, errors, and inefficiencies in the production process [5].

As automation and artificial intelligence become more prevalent, many activities that were once performed by coordinators are now performed by machines [31]. Furthermore, the increased use of artificial intelligence can lead to performance degradation, as machines are not able to replicate the same level of precision and accuracy in decision making as humans, specifically that machines do not possess the awareness to make optimal decisions [6]

Finally, the misuse of artificial intelligence could lead to a decrease in human creativity and innovation. As machines become more capable of performing tasks once done by humans, humans may become less creative and innovative [32].

2.2 Interaction between "Coordination" and "IPS":

Coordination in CPPS is the process of ensuring that all components of the IPS work together in a synchronized manner to achieve the desired outcome [29]. Coordination also ensures that the system is able to respond quickly and accurately to changes in the environment, such as changes in customer demand or disruptions in the supply chain [33].

Coordination in SPIs is typically performed by a coordinator or set of coordinators using a distributed control system [34]. These systems use a combination of sensors, actuators, and software to monitor and control the physical components of the system. The distributed control system is responsible for ensuring that all system components work together in a synchronized manner [35].

In addition to distributed control systems, coordination in CPPSs can also be achieved through the use of AI and machine learning (ML) technologies. AI and ML technologies can be used to analyze data from the physical components of the system and make decisions on how best to coordinate the system [2], [36]. For example, AI and ML technologies can be used to identify patterns in the data and make decisions on how to optimize the system for maximum efficiency.

2.3 Interaction between "IPS" and "Industry 4.0 context":

The context of Industry 4.0 has allowed for an integration and combination of advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), robotics, and cloud computing, which are all connected and integrated to create a smart factory [9]. This new technology is revolutionizing the way production systems are designed, integrated, and operated [12].

As a result, smart production systems are in need of advanced security measures such as encryption and authentication [37], and manufacturers need to ensure that their sensitive data are protected from cyberattacks. In addition, the increased integration of new I4.0 technologies causes another challenge related to security, ergonomics, and trust among operators, leading to collaboration with robots [2].

2. Challenges and perspectives

In this section, the challenges and perspectives related to the coordination of production systems are discussed. Beginning with the general context of I4.0 in which the development of intelligent production systems has been carried out, then the coordination of the production system, and finally the intelligent production system. Figure 3 provides a mapping of the issues related to coordination in intelligent production systems.

2.1 Elements related to the Industry 4.0 context

Elements related to the Industry 4.0 context. With advances in digital technology, production systems are becoming more connected, flexible and responsive. This has a major impact on the way production is managed, with a focus on data-driven decision making and automation. The impact of Industry 4.0 on the coordination of production systems is largely achieved. It is changing the way factories operate, and the skills needed to manage production.

2.1.1 Lack of resources to initiate digital transformation

Digital transformation is a transformation process that is currently occurring in many organizations around the world [38]. It is a process of integrating digital technology into all aspects of an organization, from its operations to its interactions with customers. To initiate this transformation, organizations must have the appropriate resources in place. However, many organizations lack the resources to initiate a digital transformation. They may not have the budget to invest in new digital technologies, lack the appropriate intellectual capabilities to implement these technologies effectively, or lack adequate infrastructure to implement the new technologies [39]. As a result, these organizations are at a disadvantage in regard to competing in the digital age.

2.1.2 Lack of hindsight in the face of the complexity of the subject and the technologies available

The complexity of Industry 4.0 is such that it is difficult for decision makers to step back and analyze the

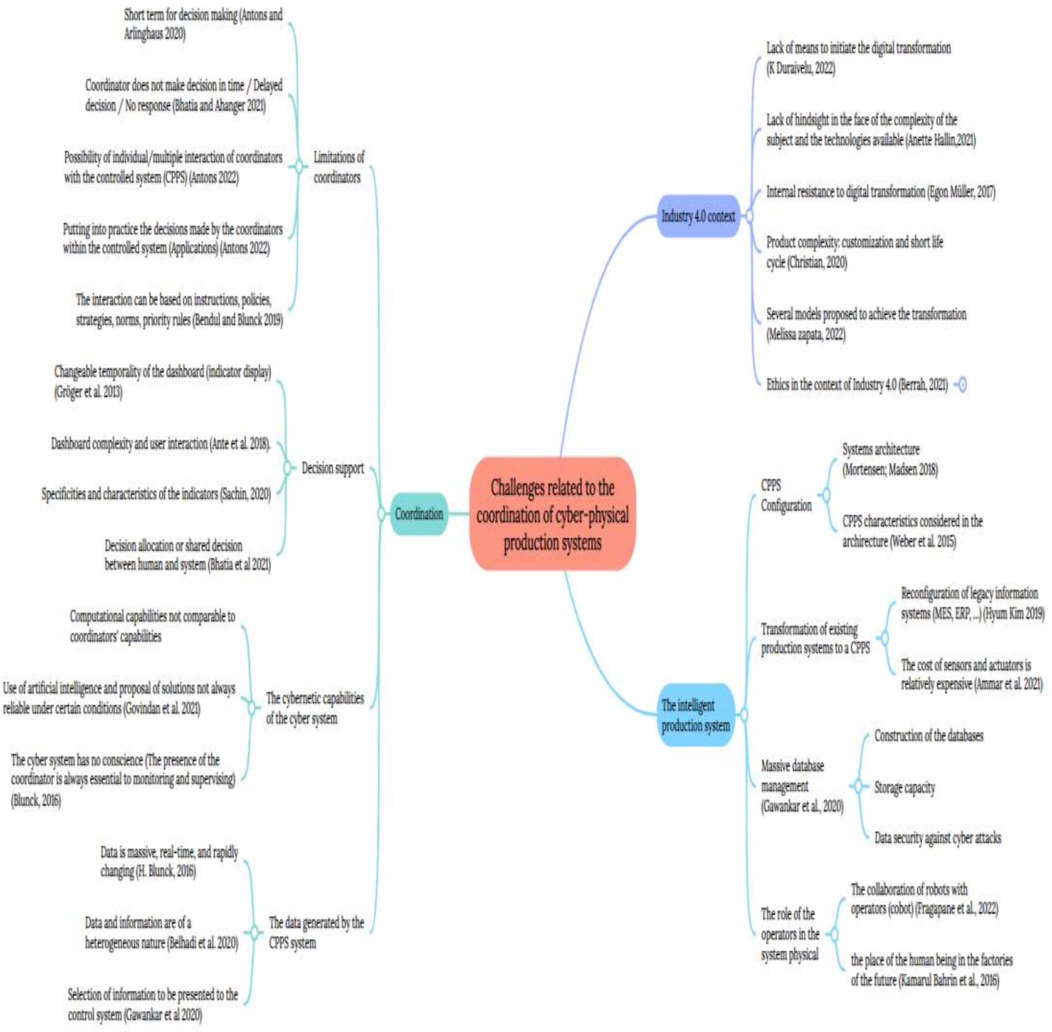

Figure 3: mapping of challenges related to coordination in intelligent production systems

situation objectively. One of the biggest challenges is the lack of a clear understanding of what Industry 4.0 actually means [40]. There is some confusion about the concept, which makes it difficult for companies to know how to prepare for it [39]. Another challenge is the lack of skills. Many of the technologies associated with Industry 4.0 are still in the design phase. Therefore, it is important to surround yourself with experts who can provide a comprehensive and objective view of the situation. Only an unbiased outside view can make the right decisions for the company's future.

2.1.3

2.1.4 Internal resistance to digital transformation

The digital transformation process is often accompanied by internal resistance from employees. This resistance can be due to several factors, including fear of change, loss of skills, and lack of understanding of new technologies. This resistance can be a major obstacle to digital

ansformation, as it can slow or even stop the process ([41]). To overcome this resistance, it is important to conduct effective communication with employees to make them aware of the benefits of digital transformation [40]. It is also necessary to provide them with adequate training so that they can master the new technologies. Finally, it is important to provide incentives for them to be motivated to adopt the new tools and change their work habits.

2.1.5 Product complexity: customization and short life cycle

Product customization and a short life cycle are factors that contribute to product complexity. Product customization means that each product is unique with its own specifications. This makes the product more difficult to manufacture and test [42]. In addition, the short life cycle means that products must be constantly improved to remain competitive [43]. This requires a continuous development and support team, which also increases product complexity.

2.1.6 Several models proposed to realize the transformation

Digital transformation maturity models are a valuable tool for organizations seeking a structured approach to improving their digital performance [44]. Several models are proposed to achieve business transformation. These models aim to help companies better understand the challenges of transformation and implement the right strategies to achieve it [45]. They also help determine the best practices to implement and the right people to engage to achieve business transformation.

Digital transformation maturity models provide a framework that can guide organizations in their efforts to become more digitally focused [46]. These models identify the different levels of digital maturity and the key areas to focus on to make progress [44]. They also provide indicators to assess progress and a roadmap to reach higher levels of maturity. Multiple models have been proposed to initiate digital transformation. Companies find themselves lost in choosing the most suitable model that aligns with the specific needs and goals of the organization.

2.1.7 Ethics in the context of Industry 4.0

This new era of I4.0 has significant ethical implications, as it will have a dramatic impact on how products are manufactured, distributed, and used [47]. The ethical issues of Industry 4.0 concern privacy and data protection, system security, resource management, and equity in access to technology [48]. Privacy is an important issue because Industry 4.0 systems collect and process large amounts of sensitive data. System security is also crucial, as cyberattacks can have consequences for businesses and consumers. Resource management is another important issue, as Industry 4.0 relies on the intense use of natural resources [49]. Finally, equity in access to technologies is a major challenge, as inequalities in access can exacerbate social and economic inequalities.

2.2 The Smart Production System

Existing industrial systems are fundamentally unsuited to CPPS. They are designed to operate with linear processes, whereas CPPSs are based on iterative processes [26]. In addition, legacy industrial systems are typically monolithic and inflexible, making them unable to adapt to the frequent and unpredictable changes of CPPSs [50]. Finally, legacy industrial systems are often very expensive to maintain and evolve, which is incompatible with the cost-efficiency goals of CPPSs.

3.2.1. CPPS configuration

Cyber-physical production system configuration is the process of configuring the physical components of a production system, such as machines, robots, and other equipment, to work with cyber components, such as software, networks, and sensors [51]. This process is paramount to the proper functioning of an intelligent production system, as it ensures that cyber and physical components are properly integrated and work together.

One of the main configuration challenges of the CPPS is the integration of physical and digital components. This requires the development of a unified system architecture that can accommodate both physical and digital components [52]. This architecture must be able to handle communication between the components, as well as data exchange between them. In addition, the architecture must be able to manage the synchronization of the components, as well as the coordination of their activities.

The configuration of a cyber-physical production system typically begins with the selection of the appropriate hardware and software components. This includes selecting the right type of machines, robots, and other equipment, as well as the appropriate software and networks [53]. Once the components are selected, they must be properly configured to ensure that they are compatible with each other and can communicate with each other. This includes configuring the appropriate communication protocols, such as Ethernet, Wi-Fi, and Bluetooth, as well as configuring the software and networks to ensure that they are properly integrated [24].

The configuration of a CPPS typically begins with the selection of appropriate hardware and software components; once the hardware and software components are selected and configured, the next step is to configure the sensors and actuators [27]. Sensors are used to detect changes in the environment, while actuators are used to control the physical components of the system. The sensors and actuators must be properly configured to ensure that they are able to detect and respond to changes in the environment.

Finally, once the configuration is complete, the system must be tested to ensure that it is functioning properly. This includes testing communication protocols, software and networks, sensors and actuators, and the physical components of the system [54].

Configuring cyber-physical production systems is a complex process that requires considerable expertise and experience. It is important to ensure that the system is properly configured and tested before it is put into production, as this will ensure that the system is able to operate effectively and efficiently.

3.2.2 Transforming Existing Industrial Systems to a CPPS

The transformation of existing industrial systems to a cyber-physical production system is an ongoing process that aims to modernize production systems and make them more flexible and responsive [55]. This process is made possible through the integration of digital technologies into production systems. This transformation allows production systems to better adapt to changes in demand and reduce lead times. It also allows for greater efficiency and productivity and improved product quality. To transform existing industrial systems into CPPSs, various factors must be taken into account. First, existing manufacturing equipment and processes must be adapted to keep up with the automation and autonomy of CPPSs. Second, the workforce must be trained to operate and maintain the CPPS. Finally, the financial and organizational aspects of the transformation must be considered.

The cost of sensors and shareholders is relatively expensive in Industry 4.0. This is partly due to the high technical specifications of these components but also to the high demand for these products in the context of Industry 4.0. Therefore, companies need to invest in advanced technologies to keep up with Industry 4.0.

3.2.3 Database Management

Database management is an important element in cyber-physical production systems. It is responsible for data storage, retrieval, and manipulation, as well as security and optimization of data access. Database management systems must be able to handle the complexity of cyber-physical production systems, as well as the real-time nature of the data. In addition, database management systems must be able to handle the large amounts of data generated by cyber-physical production systems. Finally, database management systems must be able to meet the security requirements of cyber-physical production systems. This includes the ability to protect data from unauthorized access, as well as the ability to ensure that data are not corrupted or lost.

3.2.4 The Role of the Operator

Operators in CPPSs are expected to interact and collaborate with equipment with intelligence [50]. Among this intelligent equipment, the most answered is cobots. Cobots are collaborative robots that are designed to work closely with humans. They are designed to perform repetitive and precise tasks, which can be beneficial for companies seeking to improve their productivity and efficiency [53]. However, there are some risks associated with the use of cobots. First, cobots can pose a safety risk to workers. Cobots are designed to work closely with humans, which means that the operators can be exposed to the risk of injury or death if they are not properly trained and protected [54]. This means additional costs for training operators on the safety and operation of cobots. In addition, cobots can also be prone to errors and failures. If cobots are not properly maintained and programmed, they can cause delays and errors that can negatively impact the productivity of the production system. Finally, cobots can cause cost issues [56]. Cobots are typically expensive to acquire and maintain, which can lead to additional costs for the company. In conclusion, cobots can present safety risks to operators, productivity issues, and additional costs to the company. Therefore, it is important that companies take the time to understand the risks associated with the use of cobots and take the necessary steps to minimize them.

2.3 Coordination

A cyber-physical production system (CPPS) is represented by an interconnection between a cyber-system and a (physical) production system. Moreover, this interconnection ensures real-time monitoring of production execution for intelligent decision making, thus improving industrial performance.

2.3.1 The role of the coordinator in the CPPS

The coordinator has a primary role in steering the cyber-physical production system [6]. He has interesting managerial capabilities in collaboration with the digital coordination system (F. G. N. Li, 2017); the latter makes available to the coordinator the data from the cyber system after processing.

The data generated by the system are massive data and come from a heterogeneous nature, which makes the task of the coordinator complicated [57]. The coordinator does not have enough time to process and analyse all the information and behaviour of the system, which can cause delays in decision making and even a lack of reaction [58]. In the literature, this inability of the coordinator in front of massive data is brought closer to a processing limitation, and the authors have named it the myopic behaviour [59], [60], [61]

The limitations of coordinators can be related to several activities. First, in the interaction of the coordinator with the system [62], the coordinator can declare objectives, launch action plans, and pass instructions [63]. To interact with the system, the coordinator does not have enough time to process and analyse the information and behaviour of the system [64]. Multiple locations affect the controlled system, and the location initiates instructions to drive the system ([65]. In addition, there are several types of instructions, such as coercive, limiting, directive, permissive, and influence [6]. The interaction can be instructions, policies, strategies, norms, and priority rules [35].

Second, regarding the interaction of the system with the coordinator [66], the digital coordination system provides the coordinator with massive data, which can be heterogeneous [67]. These data are in real time and change rapidly depending on the execution of the manufacturing, which can cause some limitations in the coordinator [68]. In addition, the selection of data to present to the coordination system is a delicate task (immediate, prediction, clustering, aggregated, etc.) [65].

3. Conclusion

Industry 4.0 is a new era of production that combines the use of digital technologies and intelligent production systems to improve the efficiency and productivity of production systems. Smart production systems are systems that can learn and adapt to their environment using artificial intelligence and machine learning technologies. These systems can be used to improve the design, management and control of production systems.

However, the coordination of intelligent production systems is a significant challenge. Coordination involves the scheduling and harmonious combination of system elements to achieve set goals. The coordination of smart production systems is a complex process that requires human intervention and an understanding of the constraints of coordination.

In addition, the digital transformation of production systems poses additional challenges. Intelligent production systems must be able to process data in real time and react to malfunctions. Systems must also be configured to adapt to changes in the environment and evolving technologies.

Finally, the configuration of intelligent production systems is another important challenge. The systems must be configured in such a way that they can adapt to changes in the environment.

In conclusion, the evolution of production systems in the context of Industry 4.0 poses significant challenges in terms of the coordination, digital transformation and configuration of smart production systems. These challenges require human intervention and an understanding of coordination constraints. Research on the coordination of smart production systems is therefore essential to understand and solve these problems.

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