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A SYSTEMATIC REVIEW OF THE PRINCIPLES OF INDUSTRY 4.0

BY

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Abstract. The term 'industry' is used to denote the economic sector responsible for the production of material goods, which are characterized by a high degree of mechanization and automation. The advent of industrialization has precipitated seminal technological developments in the domain of industrial engineering, which have, in turn, given rise to paradigm shifts of such profound nature that they have been termed 'industrial revolutions'.

The purpose of this paper is twofold: firstly, to identify principles applicable to organizations (smart factories) that have adopted the Industry 4.0 concept, and secondly, to explore how these principles influence the interrelationships between the concept's main pillars and technologies.

Nevertheless, no matter how the concept of Industry 4.0 is understood, it is vital to recognize that the principles, pillars and technologies associated with it

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will shape the future configuration of organizations. This will be determined by novel administrative, executive and control structures that are specific to activities related to the product/service life cycle offered to customers.

Keywords: Technologies, Pillars, Smart Manufacturing, Digital Transformation, Industrial Automation.

1. Introduction

The Third Industrial Revolution coincided with the emergence of the first electronic components, including automated processors that led to information processing (procurement, processing, storage, conversion and transmission) in particular through the use of computers (electronic calculators). This development led to the emergence of a new field related to information technology. Nonetheless, despite the fact that these processes function predominantly without the necessity for human intervention, a human element is nevertheless intrinsic to them. Consequently, with the advent of the novel concept of Industry 4.0, the digitization of production confers numerous advantages, whilst simultaneously constituting a long-term investment that will result in increased automation and reduced production times, thereby engendering enhanced economic efficiency. Consequently, the exchange of data in technologies and manufacturing processes that include cyber-physical systems (CPS), the Internet of Things (IoT), the Industrial Internet of Things (IIOT), cloud computing, cognitive computing and artificial intelligence enables the identification of the characteristics of the new Industry 4.0 concept and its trend towards automation. Consequently, it is possible to specify that these trends encompass, in addition to the monitoring of activities and equipment with an impact on production, the addressing of security and confidentiality issues.

2. Insights and perspectives on Industry 4.0

History. The industrial revolution cannot be explained by the invention or discovery of new energy sources, machines, materials or methods alone (Carvalho *et al*., 2020). However, these factors have been extremely important for economic development over the last two and a half centuries, playing a crucial role in shaping the course of history (Carvalho *et al*., 2020).

During the period preceding the first industrial revolution in the mid-18th century, the primary sources of energy were water, animal power and wood, which was the predominant building and fuel material.

The history of this concept, as shown in Fig. 1, begins with the first Industrial Revolution in Great Britain at the end of the 18^(th) century. This coincided with the development of steam engines, which made it possible to transition from manual to mechanized production methods in the textile industry. The subsequent Industrial Revolution, which took place almost a century later, was characterized by the introduction of rail transport, telegraph communications, and electricity. The third industrial revolution did not occur until after the Second World War, when the transistor was invented in the United States in 1947. This technological progress led to new advances in transport and communication technologies driven by digital computers.

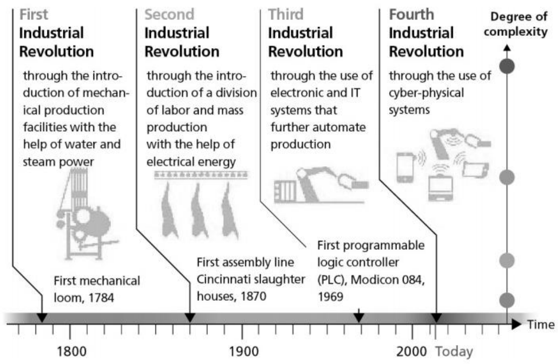

Fig. 1 – The evolution of the Industry 4.0 concept (Hozdić *et al*., 2015).

Definition. The term 'Industry 4.0' was first used in a high-tech strategic program launched by the German government in 2011. However, it was only after its adoption by the World Economic Forum in 2016 that the term began to be widely used. In comparison with previous iterations, this revolutionary development is unfolding at an exponential rate. The development of Industry 4.0 has resulted in a significant paradigm shift, with considerable ramifications for businesses and the general population. Academic research focuses on defining and understanding the concept, as well as developing the associated systems, business models and methodologies. By contrast, industry focuses on modifying industrial equipment and smart products, and identifying potential customers for these developments (Oztemel *et al*., 2020). Therefore, Industry 4.0 is the concept of a smart factory, similar to the concept of a smart city (whereby digital solutions, networks and services are used to improve efficiency for the benefit of residents and local businesses). In Industry 4.0, cyber-physical systems monitor physical processes, technologies and practices in manufacturing, making decentralized decisions to automate these industrial processes.

The pillars of Industry 4.0. It is evident that throughout the initial three industrial revolutions, individuals observed and cultivated mechanical, electrical, and computer technologies with the objective of enhancing the efficiency of industrial processes. The fourth industrial revolution, however, is predicated on the development of production methodologies founded on data exchange and the establishment of a malleable industry. This endeavor enables manufacturers to respond adroitly to the demands of consumers through mass customization, often resulting in a plethora of efficiencies (Sharma *et al*., 2021). The concept of Industry 4.0 denotes a paradigm shift in manufacturing, characterized by the integration of information-intensive processes. The integration of digital technology with big data, real-time data and the use of IoT-enabled industrial assets is essential for creating a more efficient and connected ecosystem. The integration of Industry 4.0 technologies within corporate entities has the capacity to effect a paradigm shift in their manufacturing processes, thereby engendering novel services and business models that capitalize on their inherent connectivity. In the context of the fourth industrial revolution, new technologies have emerged that facilitate the automation of production processes and enable individuals to make informed decisions by leveraging real-time data and internet-connected equipment. This enables the proactive prevention of significant issues before they arise. The majority of authors subscribe to the view that Industry 4.0 is developing on the basis of nine technological pillars, presented in Fig. 2, which create a link between the digital and real (physical) worlds and create autonomous and intelligent systems. The nine pillars of Industry 4.0 have been developed to transform isolated and optimized production cells into a fully integrated, automated and optimized production flow (Vaidya *et al*., 2018).

Fig. 2 – The Nine Pillars of Industry 4.0 (Chitariu *et al*., 2024).

The main pillars of Industry 4.0 are:

- Augmented reality (AR) is a technology that combines the real world with elements from the virtual world. These elements are superimposed on a real environment in real time. In the context of substantial industry transformations, it is imperative for companies to adopt and integrate novel technologies. In recent years, an increasing number of companies have adopted these new technologies, as illustrated in Fig. 3, with the objective of implementing the Industry 4.0 concept. In the context of Industry 4.0, augmented reality (AR) can be defined as the integration of additional computer-generated information into a real environment.

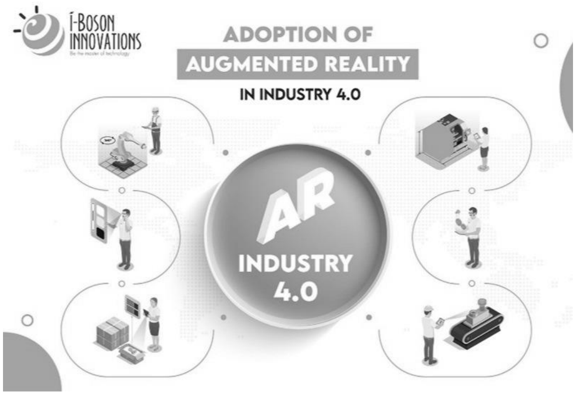

Fig. 3 – AR in Industry 4.0 (iBoson Innovations 2021).

- System Integration. The team coordinated by the German Federal Ministry of Education and Research (BMBF) for Industry 4.0 has identified the following aspects relating to system integration, among others:
  - horizontal integration through value networks;
  - vertical integration of production systems into networks;
  - end-to-end digital integration of technology throughout the value chain (Mazak *et al.*, 2015).

Figure 4 shows a brief description of the system integration.

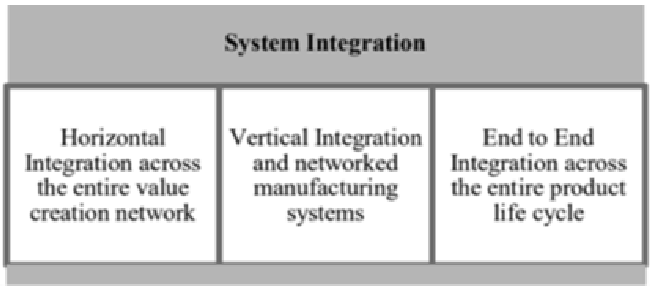

Fig. 4 – System Integration (Vaidya *et al.*, 2018).

- Cloud Computing is an information technology that employs a network of servers for the storage, management and processing of data. This technique has the potential to be advantageous for manufacturers, as it enables the provision of rapid and targeted data for any sales situation. By storing information about a product's history from the moment it is ordered to the moment it is actually sold, the time required to manufacture a customised version according to customer requirements can be reduced. The advent of ubiquitous information access has engendered a paradigm shift in sales processes, thereby engendering greater flexibility (Gillich *et al*., 2017).
- Big Data is the professional solution for analysing large amounts of data. Consequently, big data analytics tools represent a suitable solution for Industry 4.0, facilitating the cleaning, formatting and transformation of industrial data. As illustrated in Fig. 5, the four-'V' model of industrial big data is demonstrated (Khan *et al*., 2017). The accumulation of this data can also be used to identify production trends, patterns and relationships between inputs and outputs that can be used to improve work platforms.

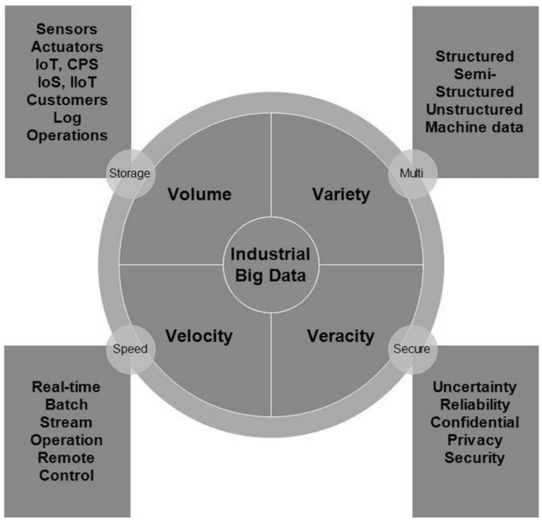

Fig. 5 – Industrial Big Data (Khan *et al*., 2017).

- Internet of Things (IoT) can be defined as the virtual interconnection of a large number of smart devices to generate an improved user experience of products (Fig. 6). According to some authors, the Internet of Things (IoT) can be defined as a network of uniquely addressed objects, interconnected globally, based on standardised communication protocols. This enables the integration of any physical or virtual entity that 'exists and moves in space and time and can be identified by assigned identification numbers, names and/or location addresses' into communication networks, thereby categorizing it as a “thing” (Lampropoulosand *et al*., 2019).

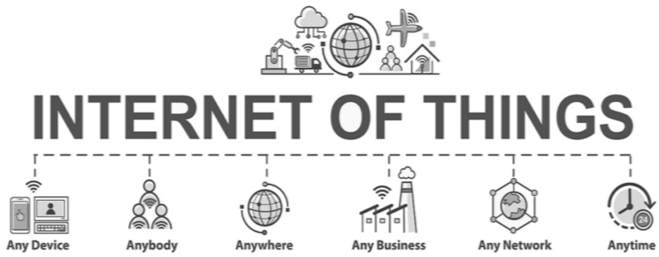

Fig. 6 – Internet of Things(IoT) (Paige West, 2023).

- Additive manufacturing is a layer-by-layer printing process invented in 1987 that uses the principle of layer-by-layer integration of materials. This technology facilitates the fabrication of a physical object, which can reproduce either the three-dimensional digital model of the object or the three-dimensional model of the object created in CAD software. This is achieved by depositing the constituent material in a layered manner using a computer-controlled processing tool (Ashima *et al*., 2021). Additive Manufacturing can thus be defined as a computer-assisted process for forming a solid three-dimensional object of any shape, achieved through an additive process, i.e. by superimposing successive layers of material.
- Cyber Physical Systems (CPS) are defined as the set of physical objects, devices, machines and entire entities that are connected to each other in an internal network or on the Internet. These systems communicate in real time with each other and with human users. They are capable of storing, processing and transmitting information outside the physical body, thus acquiring a new identity in the form of a virtual representation in the network (CPS – Cyber Physical Systems). Conversely, other authors define these systems as industrial systems, automation systems that enable multiple innovative functionalities through networks and their access to the cyber world, thus significantly changing our daily lives (Jazdi *et al*., 2014). A concise overview of CPS is provided, as illustrated in Fig. 7.

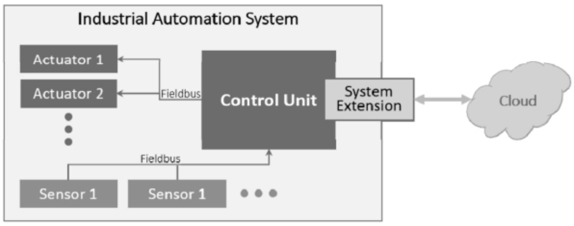

Fig. 7 – Cyber Physical Systems (Jazdi *et al*., 2014).

- Advanced robotics, otherwise termed "intelligent robots", are devices that operate either wholly or partially autonomously. They are capable of physical interaction with both humans and the environment and are able to modify their behaviour based on the data received via sensors. As illustrated in Fig. 8, robotics has considerable potential in manufacturing and associated domains, with significant applications for Industry 4.0 (Javaid *et al*., 2021).

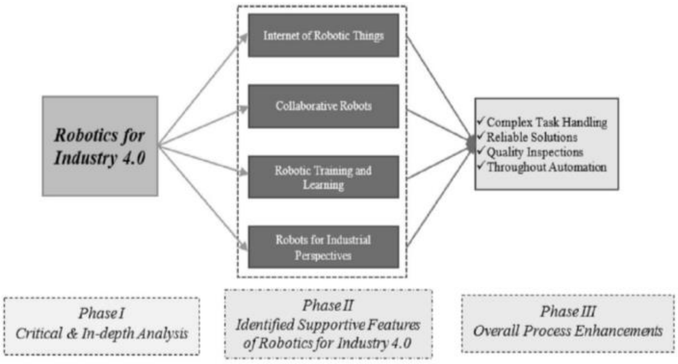

Fig. 8 – Applications of robotics for Industry 4.0 (Javaid *et al*., 2021).

- Simulation/Digital Twin – Digital Twin is defined as the capability to virtually replicate and enhance a product or manufacturing process. The distinction between CAD-CAM-CAE and Digital Twin lies in the latter's objective to meticulously document, systematise, and synchronise a comprehensive array of product-related data. This encompasses the conceptualisation phase, design, manufacturing, launch, utilisation, maintenance, and eventual decommissioning, extending to the recycling stage. The concept model proposed in Industry 4.0 for understanding how Digital Twin works is illustrated in Fig. 9 and comprises a six-step approach that includes creation, communication, aggregation, analysis, insight and action (Pires *et al*., 2019).

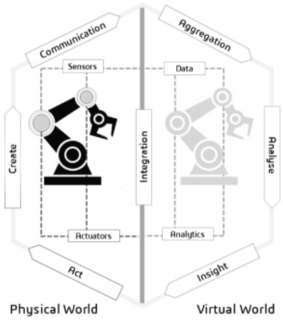

Fig. 9 – Digital Twin - functional model (Pires *et al*., 2019).

3. The principles of Industry 4.0

The design principles of Industry 4.0 facilitate the integration of various Industry 4.0 technologies by system and application designers for the successful development and implementation of sustainable Industry 4.0 systems. A review of the literature reveals the identification of six key design principles: interoperability, virtualisation, decentralisation, real-time capabilities, service orientation and modularity.

Within the domain of industrial engineering, the tenets of Industry 4.0 offer a indirect description of the smart factory, whilst concomitantly proposing the incorporation and utilisation of minimum functional requirements. The aforementioned requirements, in conjunction with prevailing technological capabilities, are founded on the six fundamental principles enumerated above and illustrated in Fig. 10. This comprehensive framework also gives rise to the conceptualisation of the smart factory.

Fig. 10 – Principles of Industry 4.0 (Agrawal *et al*., 2024).

The published literature has identified and presented several fundamental principles that underpin the concept of Industry 4.0, the industrial revolution characterized by advanced digitization, interconnectivity and intelligent automation. The following principles are most frequently mentioned interconnection, virtualization, decentralized, real-time capability, service orientation, flexibility.

3.1. Interconnection

Interconnection (interconnection or interoperability) is defined as the ability of machines, devices, sensors and people to connect and communicate with each other. The concept of interoperability can be realised through the utilisation of various tools (enablers), including the Internet of Things (IoT), the Internet of People (IoP) and the Internet of Everything (IoE), amongst others (Dikhanbayeva *et al*., 2020). At the organisational level, the architectures, standards, concepts and other elements that require integration are defined. Simultaneously, the application level establishes the overarching principles that govern the utilisation of methods, models, standards, and other elements (Chimsom *et al*., 2019). From a technical perspective, a range of tools, platforms, and infrastructures are integrated to support various I4.0 technologies (Chimsom *et al*., 2019). This, in turn, enables interoperability between different technologies. It can thus be concluded that the choice of communication methods and languages is determined by the semantic level in different integrated architectures (Chimsom *et al*., 2019). The following section will present a number of manufacturing companies that have adopted data interoperability as a means to enhance their production efficiency:

- General Electric (GE): General Electric's (GE's) involvement with the Industrial Internet of Things (IIoT) has been characterised by its utilisation of data interoperability protocols. GE has implemented the Predix platform to connect its machinery and devices across various facilities, utilising open standards such as OPC UA. The aforementioned interconnectedness has facilitated the implementation of predictive maintenance, the streamlining of supply chains, and the enhancement of overall equipment effectiveness (OEE) (Data Dynamics, 2025).
- Bosch: In its role as a leading global supplier of technology and services, Bosch has adopted a data interoperability strategy with the aim of enhancing its manufacturing processes. The company utilises standardised communication protocols to interconnect its diverse range of products and systems. This strategic initiative by Bosch has culminated in the enhancement of its production line synchronization, leading to substantial reductions in cycle times and optimisations in resource utilisation (Data Dynamics, 2025).

- Procter & Gamble (P&G): P&G, a colossus of the consumer goods industry, has employed data interoperability to enhance its supply chain and manufacturing operations. P&G's capacity to forecast demand with greater precision is predicated on the integration of data from multiple sources, encompassing suppliers and production facilities. This comprehensive approach enables the company to ensure the timely replenishment of raw materials. This approach has been demonstrated to result in a reduction in inventory costs and an enhancement in production efficiency (Data Dynamics, 2025).
- Ford Motor Company: Ford has adopted a data interoperability strategy to facilitate a more connected and efficient manufacturing ecosystem. The adoption of IoT technologies and standardised communication protocols by Ford facilitates the real-time monitoring and control of various aspects of its manufacturing processes. The consequence of these actions has been an enhancement in the quality control measures implemented, a reduction in the amount of waste, and an improvement in the efficiency of the operational processes (Data Dynamics, 2025).

  The concept of data interoperability is pivotal in this context, as it facilitates the transformation of manufacturing floors into interconnected ecosystems, thereby promoting efficiency and collaboration.

3.2. Virtualization

Virtualisation can be defined as a process that combines physical production systems, their digital equivalents and process data to create a virtual factory environment. This environment is capable of monitoring, controlling, simulating physical systems and processes, sending data to update the virtual model in real time, diagnosing and anticipating faults, and guiding employees in performing maintenance (Dikhanbayeva *et al*., 2020). The implementation of virtualisation confers numerous benefits, encompassing the conceptualisation and execution of Industry 4.0 semantic models, the design of prototypes and the subsequent evaluation thereof, the facilitation of workforce training and education, and the incorporation of customers (i.e. end users) in the design process of products (Chimsom *et al*., 2019).

The utilisation of virtualisation has been shown to facilitate the operations of managers and organisations in a number of ways.

- The process of minimising downtime and facilitating disaster recovery has been rendered more straightforward and pragmatic through the implementation of virtualisation. This technological advancement has rendered the process of recreating or duplicating a server or virtual machine more expeditious and pragmatic in the event of a disaster or emergency (Mohanan, 2023).

- The enhancement of productivity and efficiency is achieved through the optimisation of IT infrastructure and hardware management, which is facilitated by a reduction in the number of servers. This virtual environment offers managers the capability to streamline the process of implementing updates, thereby obviating the need for manual intervention on each individual server. Instead, they are empowered to leverage the virtual environment's accessibility to orchestrate changes across all virtual machines (Mohanan, 2023).
- The utilisation of a virtual environment has been demonstrated to facilitate enhanced testing procedures. This virtual environment provides a secure and isolated space for developers to conduct their testing activities without causing disruption to other operational processes. The capacity to replicate a virtual system and execute all requisite tests is a key capability. It is important to note that, since virtual machine work is automatically saved as a snapshot or backup, any errors that may occur during testing can be rectified by reverting to the previous version (Mohanan, 2023).

3.3. Decentralized

Decentralized decisions refer to the capacity of cyber-physical systems to autonomously formulate and execute decisions, thereby ensuring maximum independence from external intervention. Nevertheless, the principle of decentralization cannot be observed solely in machines, as it also pertains to the autonomy granted to individuals as partners in Industry 4.0. They possess greater autonomy to identify issues, analyses parameters and make decisions whenever necessary, with the aim of promoting the common good for their area of activity in industry as well as for its integrity (Carvalho *et al*., 2020). Consequently, from a technical standpoint, the decentralization of decision-making processes is facilitated by the existence of CPS. Furthermore, the integration of computers, sensors and agents into these devices will facilitate autonomous monitoring and control of the physical environment. (Hermann *et al*., 2016).

The aim of decentralization is to achieve the following benefits:

- Organizations become self-sufficient – with decentralization, the pressure is distributed across all levels. Consequently, the absence of a team member does not greatly impact overall productivity. Consequently, even top management can take days off, meaning the organization is self-sufficient.
- Scaling up is easier since the top management does not need to get involved in the day-to-day operations of a particular location. Management can easily hire capable local employees to handle day-to-day functions, helping them to grow the business overall without getting stuck in micromanagement (Notchup Team, 2022).

- Decentralization gives managers at all levels of the organization autonomy, enabling faster decision-making. This means that employees do not need to wait for approvals from senior management before taking on a task. This helps with faster decision-making, which increases overall productivity (Notchup Team, 2022).
- Happier team members and business owners: The basic principle behind decentralization is to empower and motivate employees at all levels. This enables them to find meaning and motivation through their work. This, in turn, keeps team members and business owners happy (Notchup Team, 2022).
- Strengthening leadership skills: giving individuals the power to make decisions based on their own experience and wisdom helps to develop leadership qualities. This helps to build better leaders for the future (Notchup Team, 2022).
- Motivating subordinates - When employees know they are valued and their skills are developing in a well-rounded manner, their motivation increases. Furthermore, this approach can also help to increase the business's employee retention rate (Notchup Team, 2022).
- Efficient communication: Since decision-making power flows at all levels, communication channels become more transparent and efficient for everyone. This improves clarity around tasks and helps form relationships that would not be possible within a hierarchical, centralized organizational structure (Notchup Team, 2022).

3.4. Real-time capability

The integration of real-time capability, facilitated by the capacity to collect and analyses current data in real-time, and the adoption of a modular configuration, enables the smart factory to respond in real time to changes occurring within and outside the factory. The utilization of Cloud Computing and Big Data can serve as optimal instruments for real-time data analysis and processing, with integrated analytics systems that facilitate the identification of bottlenecks within the supply chain (Dikhanbayeva *et al*., 2020). This approach is predicated on the identification of defects and the necessity of maintenance, with the objective of optimizing the process and increasing productivity (Dikhanbayeva *et al*., 2020). Consequently, Industry 4.0 collects and analyses data from various sources in order to identify patterns, make predictions and improve production decisions. There are many benefits to real-time processing, including improving customer experience and enabling better business decisions.

Here are some of the important benefits of processing your data in real time:

- Immediate Insights and Decision-Making - Real-time processing facilitates the acquisition of rapid insights and the formulation of decisions based on the most recent data available. This capability enables business leaders to respond to events and changes as they occur. Furthermore, real-time processing facilitates enhanced team collaboration and communication in real-time. This enables companies to respond more quickly to changing market conditions and customer requests (Richman, 2025).
- The enhancement of data quality and accuracy through real-time processing - The utilization of real-time processing has been demonstrated to facilitate the identification and rectification of errors and inconsistencies in a timely manner, thereby ensuring the integrity and precision of data. The utilization of real-time processing has been demonstrated to enhance the accuracy of data within the retail and manufacturing sectors. Real-time processing facilitates the following: The identification and rectification of errors in customer records is imperative, as is the maintenance of accurate stock inventory data. It is imperative to closely monitor the performance of production equipment (Richman, 2025).
- The Optimization of the Customer Experience - The utilization of real-time processing within customer service systems has been demonstrated to enhance the customer experience. Real-time processing enables firms to evaluate client data instantaneously and generate recommendations that are pertinent and appealing. In the context of retail, real-time processing facilitates the personalization of products, services and marketing to individual customers, the tracking of customer preferences, and the proposal of customized products and services. It is submitted that businesses may enhance sales and revenue by offering individualized recommendations and experiences (Richman, 2025).
- Real-time Monitoring and Control -Real-time processing facilitates real-time system monitoring and control. Businesses and agencies are able to identify potential issues and respond promptly by processing and analyzing data in real time. In the field of manufacturing, for instance, it facilitates real-time monitoring and control of manufacturing operations. By collecting and analyzing data, manufacturers can identify issues with equipment or processes as soon as they arise and rectify them promptly. This has been demonstrated to reduce downtime and increase efficiency and production (Richman, 2025).
- Enhanced Security and Fraud Detection - Real-time processing facilitates the identification of fraudulent activity and enhances the security of business systems. By processing and analyzing data in real time, businesses can prevent data breaches and other security problems (Richman, 2025).

3.5. Service orientation

Service orientation is a design principle that entails a shift in focus from product-oriented sales to product - and service-oriented sales. Consequently, smart factories will transition towards a service sales strategy, signifying that in addition to designing and manufacturing products, they will also create associated services to be sold in conjunction with their products. In this manner, Industry 4.0 maintains the efficacy of its network of partnerships with all stakeholders, whether they be customers, industrial partners or suppliers (Carvalho *et al*., 2020). It has been demonstrated that universal access to services, products and relevant information regarding production is facilitated through both virtual and physical platforms (Carvalho *et al*., 2020; Ortiz *et al*., 2020).

The following section sets out some key reasons for transitioning towards a service-oriented business model:

- The generation of revenue may take place at various points in time, and the nature of the revenue may be either one-time product sales or continuous revenue streams (Hiisilä, 2023).
- The establishment of competitive advantage, in addition to the circumvention of the so-called 'commodity trap', constitutes a fundamental imperative for any business entity aspiring to thrive in the contemporary economic climate (Hiisilä, 2023).
- The provision of value-added services has been identified as a key factor in the creation of distinctive customer experiences (Hiisilä, 2023).
- This is achieved in part by increasing customer satisfaction and retention (Hiisilä, 2023).
- The necessity of adapting to changing market demands is becoming increasingly apparent (Hiisilä, 2023).
- It is vital for businesses to provide support for the customer sustainability objectives which have been established (Hiisilä, 2023).
- The utilization of opportunities engendered by technological advancements (Hiisilä, 2023).
- The determination of value through the analysis of ecosystems and networks (Hiisilä, 2023).

3.6. Modularity

Flexibility (modularity) is defined as the ability to adapt quickly and smoothly to changes and trends in industrial manufacturing practices. The integration of industrial robotics, additive manufacturing, augmented reality and virtual reality has the potential to facilitate the development of modular systems, thereby enhancing agility and flexibility within industrial contexts (Dikhanbayeva *et al*., 2020). However, the integration of modular systems with Big Data, IoP and industrial simulation applications facilitates the analysis of customer and market trends, leading to the streamlining of customized processes and the subsequent transformation of these processes into a revenue stream for the company (Dikhanbayeva *et al*., 2020).

When a method is being considered for guiding and supporting modularization work, the following points should be noted:

- Establishing a comprehensive and precise understanding of the customer's requirements and the specific characteristics of the application (Johansson, 2024).
- The process of ascertaining the requirements of all relevant stakeholders, both within and without the organization (Johansson, 2024)
- Creating connections between different functions and linking them to the needs of stakeholders (Johansson, 2024).
- Determining the interfaces between modules that are of paramount importance from a strategic standpoint (Johansson, 2024).
- Comprehension of the manner in which computer programs and physical components cooperate to deliver solutions (Johansson, 2024).

Advantages and disadvantages. When analyzed through the lens of Industry 4.0, these principles offer the field of industrial engineering both significant opportunities and complex challenges. One of the challenges posed by this novel concept relates to the workforce. However, it is not only the Industry 4.0 concept but also all three previous industrial revolutions that have had a significant impact on countries' economies. Concomitant with their enhanced efficiency, which has facilitated economic growth, these revolutions have exerted an influence on the structure of industries and, consequently, on the composition of the workforce, whose roles have undergone substantial evolution over the past century. Another challenge proposed in the context of the pillars and principles of this concept relates to energy savings and the environment. In this regard, the technological innovations of the fourth industrial revolution appear to be progressing in this direction, as the optimization of manufacturers' production tools can result in a substantial reduction in energy wastage. Another challenge pertains to the threats to cyber security in the context of new technologies, attributable to the negligence of employees who are not yet sufficiently aware and therefore expose their industry to accidental leaks. The risk of such leaks is increased by the fact that working from home means that problems are not detected in time by workers because they are not on site.

In terms of opportunities, it should be noted that Industry 4.0 places a strong emphasis on the direct and dynamic relationship between producer and consumer, who are considered the two main actors in the new digitalized industrial model. In this context, the roles of these professionals are evolving and becoming interconnected in a manner that is significantly more profound than is the case in traditional industries.

4. Conclusions

This paper makes a contribution to the current debate on the concept of Industry 4.0, both within academic circles and in industry. By analysing emerging trends, the dynamic relationship between producers and consumers, and the impact of new technologies on production processes, the study offers relevant insights for researchers, practitioners and decision-makers. In this context, it is important to note that the report highlights not only the technological transformations, but also the organisational and social changes accompanying the transition to smart factories and the connected economy. The paper's objective is twofold: firstly, to provide a theoretical foundation for the Industry 4.0 concept and, secondly, to explore its practical applications in the context of industrial digitisation and innovation strategies.

Concurrently, the paper contributes to the consolidation of a shared understanding of the concept of Industry 4.0 through its analysis of the design principles associated with it, a prerequisite for a coherent and well-founded scientific debate. Moreover, these principles offer a valuable reference framework for academic inquiry, thereby facilitating the identification, description and selection of pertinent scenarios in the domain of Industry 4.0 for future research exploration.

It is therefore possible to consider the following practical contributions of the article:

- the study elucidates the significance of comprehending the historical progression of the concept of 'Industry 4.0'. It meticulously delineates the stages of industrial evolution that culminated in the emergence of this novel model.
- the study provides a coherent and updated definition of the concept, drawing upon specialised literature and exploring the main pillars of Industry 4.0 from the perspective of recent technological developments. These developments have direct relevance to the field of industrial engineering. Pillars of this paradigm include digitisation, automation, artificial intelligence, the Internet of Things (IoT), robotics and additive manufacturing. Collectively, these technological advancements are instrumental in the fundamental transformation of industrial processes, encompassing their design, management and optimisation.
- the most significant contribution is the identification and description of the fundamental principles of the Industry 4.0

concept. These principles are based on information from the specialised literature, and the text highlights how these principles underpin the digital transformation of production systems. This analysis provides an in-depth understanding of how emerging technologies influence industrial processes, contributing to the development of intelligent, flexible and efficient systems.

It is therefore evident that in order to ensure the successful integration of these principles, both understanding and implementation are essential. This is not only a technological necessity, but also a strategic condition for increasing competitiveness in modern industrial engineering. In future research, issues such as the integration of sustainability, industrial data management and the adaptation of human capital to new technological requirements could be explored.

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O ANALIZĂ SISTEMATICĂ A PRINCIPIILOR INDUSTRIEI 4.0

(Rezumat)

Termenul „industrie" este utilizat pentru a desemna sectorul economic responsabil de producţia de bunuri materiale, care se caracterizează printr-un grad ridicat de mecanizare şi automatizare. Apariţia industrializării a precipitat dezvoltări tehnologice seminale în domeniul ingineriei industriale, care, la rândul lor, au dat naştere la schimbări de paradigmă atât de profunde încât au fost denumite „revoluţii industriale".

Scopul acestui document este dublu: în primul rând, identificarea principiilor aplicabile organizaţiilor (fabricilor inteligente) care au adoptat conceptul Industrie 4.0 şi, în al doilea rând, explorarea modului în care aceste principii influenţează interrelaţiile dintre pilonii principali ai conceptului şi tehnologiile.

Cu toate acestea, indiferent de modul în care este înţeles conceptul de Industrie 4.0, este esenţial să se recunoască faptul că principiile, pilonii şi tehnologiile asociate acestuia vor modela configuraţia viitoare a organizaţiilor. Aceasta va fi determinată de structuri administrative, executive şi de control inovator, specifice activităţilor legate de ciclul de viaţă al produselor/serviciilor oferite clienţilor.