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MANUFACTURING IN INDUSTRY 4.0 TOWARD INDUSTRY 5.0

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Abstract: *The paper examines the transition from Industry 4.0 to Industry 5.0, focusing on significant transformations in manufacturing. While Industry 4.0 emphasizes digital connectivity, automation, and data-driven smart personalization, Industry 5.0 reintroduces human collaboration and sustainable practices, aiming for adaptive cognitive manufacturing systems. This new paradigm leverages advanced technologies like AI, smart sensors, blockchain, and digital twins to enhance efficiency, innovation, and human-centered approaches. The article outlines the evolution of production paradigms, moving from mass production to mass personalization, driven by big data and smart systems. It also highlights the development of smart manufacturing systems, including the integration of smart tools, real-time monitoring, and data analysis frameworks, alongside steps to implement sustainable, customized, and flexible production processes.*

Keywords: *Industry 4.0, Industry 5.0, Smart Manufacturing, Smart Personalization, Smart Manufacturing System, Integrated System, Adaptive Cognitive Manufacturing*

1. INTRODUCTION

In the third millennium, in which we find ourselves, we are witnessing profound changes in the economic, social, and geopolitical environment. Crises alternate with economic growth, the COVID-19 pandemic has determined a different way of perceiving labor and human relations, and regional conflicts have caused human and labor migration, all of which, and others, foreshadow a different world hierarchy [1].

In this context, production systems are constantly evolving. Customers now play a bigger role in decision-making as a result of the move from mass and serial production to mass personalization and individualization brought about by the diversification of consumer and market requirements. Big data is now used in smart personalization to better understand client needs and increase design productivity and efficiency.

Products have also become increasingly complex, incorporating new functions and more intelligence, moving from modular architecture to open architecture [2].

In relation to these, there is also an evolution of manufacturing systems, from flexible systems to smart reconfigurable systems, to adaptive cognitive manufacturing systems [1].

More and more businesses are being forced to convert production unities into smart factories in order to meet the new requirements established by a market that is continuously evolving due to the latest wave in the industry's technical progress.

Based on bibliographic research, the paper aims to review all these changes that define manufacturing in Industry 4.0 toward 5.0, from the evolution of technology and production paradigms to smart manufacturing and data-driven smart manufacturing systems to adaptive cognitive manufacturing systems.

2. INDUSTRIAL FRAMEWORK

2.1 Evolution technique

At the close of the 18th century, the first industrial revolution was documented, and it was distinguished by the introduction of mechanical production equipment powered by water or steam. The second industrial revolution began at the end of the 19th century and represented the transition to mass production, using electrical equipment and the division of labor. The 1980s saw the start of the third industrial revolution as computers were used to automate production machinery. The fourth industrial revolution, most often found in Europe under the name "Industry 4.0", involves a set of advantages from the perspective of developing a new product with economic implications and benefits, throughout the distribution value chain [3, 4]. The characteristics of industrial revolutions are shown in Figure 1.

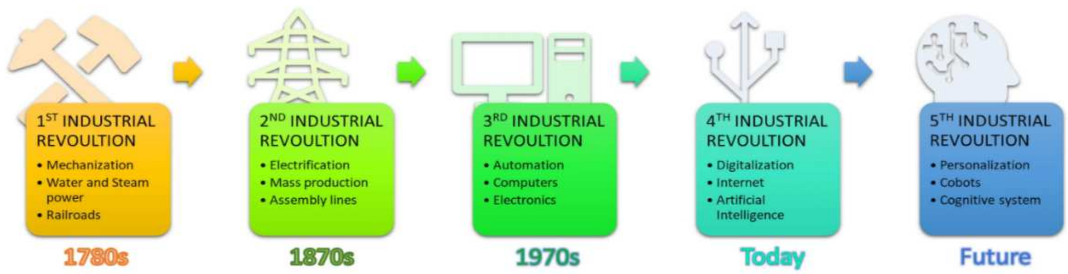

Fig. 1. Different stages of the Industrial Revolution [5].

New technologies (Fig. 2), such as Big Data and Analytics (BDA), Autonomous Robots, the Industrial Internet of Things (IIoT), Cloud Computing (CC), Cybersecurity, Additive Manufacturing (AM), Cyber-Physical Systems (CPS), and Augmented Reality (AR), define the fourth industrial revolution (Industry 4.0) [5].

While the world continues to adapt and achieve the possibilities of Industry 4.0, some scientists and industrialists have begun to anticipate and discuss Industry 5.0, the next industrial revolution. Industry 5.0 is believed to focus on sustainable production while reintroducing human input into manufactured goods and bringing people back into the game for collaboration. Industry 4.0, on the other hand, describes how digital links between machinery allow for constant data flow and ideal optimization [6].

Fig. 2. Technologies specific to Industry 4.0 [6].

Artificial Intelligence (AI), Machine Learning (ML), the Internet of Everything (IoE), Artificial Intelligence of Things (AIoT), Digital Twin (DT), Collaborative Robots-cobots, Smart Sensors, Blockchain, Edge and Fog Computing, Cognitive computing, 6G and beyond, Augmented reality, mixed reality, and holography are the technologies (Fig. 3) that are leading towards Industry 5.0 [5, 7].

Fig. 3. Industry 5.0's Prospective Technologies [5].

Since over two-thirds of industries have yet to implement Industry 4.0, they may be able to switch straight to Industry 5.0 technology. A comparison of Industry 4.0 and Industry 5.0 technologies is presented in Table 1 [5].

Table 1

Comparison between Industry 4.0 and Industry 5.0 technologies [5].

S#	Industry 4.0 technologies	Industry 5.0 technologies
1	Mass customization	Mass personalization
2	Highly automated autonomous systems	Individualized human-machine interactions
3	Automation and Industrial robots	Intelligent automation, Collaborative robots
4	Artificial intelligence, Machine learning	Cognitive computing
5	Internet of Things (IoT), Industrial Internet of Things (IIoT)	Internet of Everything (IoE), Artificial Intelligence of Things (AIoT)
6	Cloud computing	Edge computing, Fog computing
7	Simulations	Digital twins
8	Centralized traditional databases	Decentralized blockchain
9	LAN, Internet	Ultra-low latency high speed internet
10	Virtual reality	Extended reality (AR, MR, Holography) and Metaverse

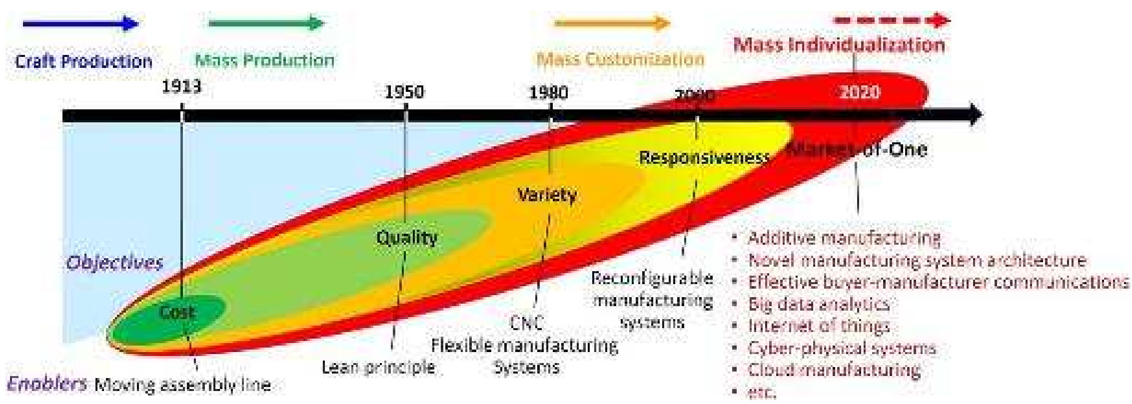

Fig. 4. The evolution of production paradigms, their objectives and drivers [8].

2.2 Production paradigms

The industrial environment is facing a paradigm shift that will massively influence production. In this sense, a shift is observed from mass and personalized production to mass individualized production [8].

High levels of design creativity and production flexibility are necessary for highly complex goods that fulfill several, customized purposes.

Figure 4 presents a timeline showing the evolution of production paradigms from artisanal production to mass individualization. Five ellipses illustrate the objectives of different production paradigms, including cost, quality, variety, responsiveness, and market of one, as well as their corresponding supporting factors.

In the context of Industry 4.0, there has recently been talk of the emerging paradigm of data-driven smart personalization [9].

Smart personalization uses big data to enhance productivity, design efficiency, and consumer understanding.

As shown in Table 2, smart personalization and mass personalization are differentiated by three characteristics: the driving force of the decision-making process, responding to demand uncertainty, and customer relationship.

Table 2

Comparison between mass personalization and smart personalization [9].

Features	Mass personalization	Smart personalization
The driving force of the decision-making process	Designers' experience and domain knowledge	Big data
Responding to demand uncertainty	Passive, which puts pressure on suppliers	Predictable and proactive, improving coordination
Customer relationship	Limited personalization options, limited customer participation	User interaction, open innovation

3. SMART MANUFACTURING

Manufacturing has been significantly impacted by developments in internet technology, including the Internet of Things (IoT), cloud computing (CC), big data (BD), and artificial intelligence (AI). The amount of data being gathered is growing. BD presents a fantastic chance to switch from the current manufacturing paradigm to smart manufacturing. Businesses can become more competitive by implementing data-driven strategies thanks to BD. The goal of smart manufacturing is to turn data collected throughout a product's lifecycle into intelligence that will benefit every facet of production [10]. Big data produced by manufacturing operations may often be divided into the following categories:

Management data collected from production information systems (MES, ERP, CRM, SCM, and PDM).

Equipment data is collected from smart factories by *Industrial Internet of Things* (IIoT) technologies, which includes data related to real-time performance, operating conditions, and maintenance history of manufacturing equipment.

Public data obtained through open databases, related to intellectual property, infrastructure, social development, environmental protection, and health.

The production module, data driver module, real-time monitoring module, and problem processing module are the four components that make up the data-driven smart manufacturing framework, as seen in Figure 5.

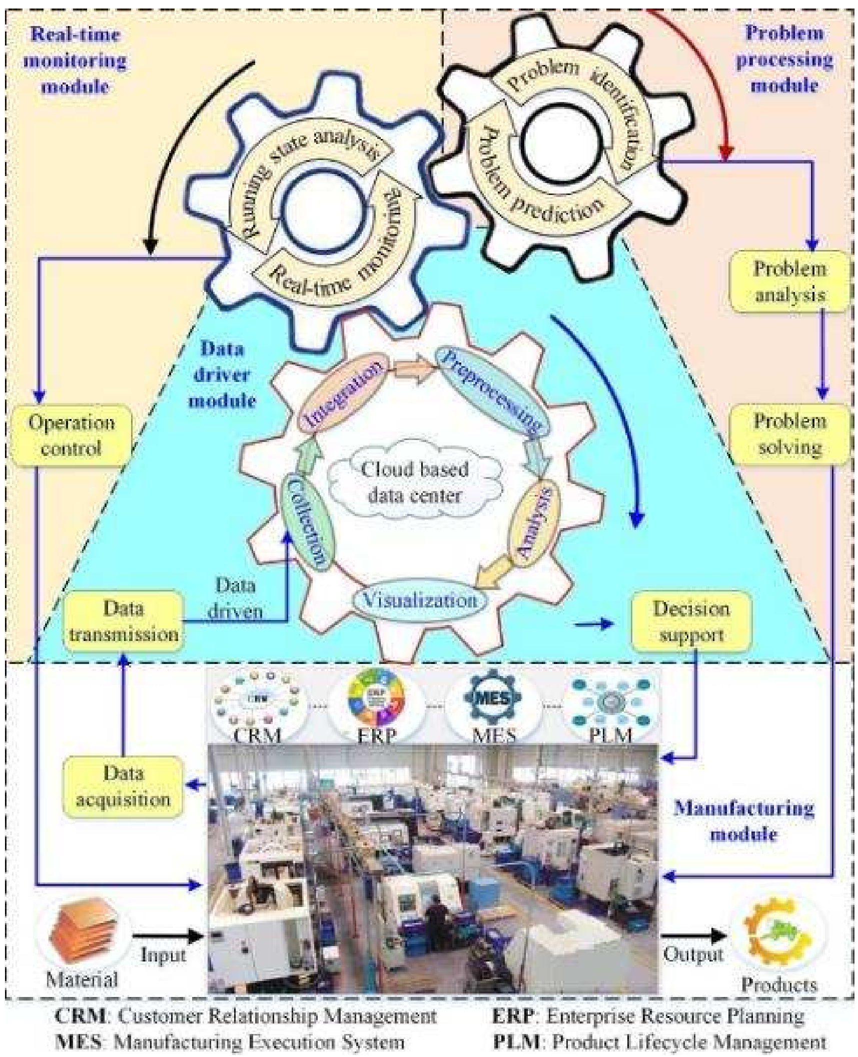

Fig. 5. Data-driven smart manufacturing framework [10].

The manufacturing module accommodates a range of manufacturing operations. It encompasses a variety of industrial resources and information systems and can be summed up as man-machine-material-environment.

The data driver module serves as the impetus behind smart manufacturing across the industrial data lifecycle.

The real-time monitoring module contributes to real-time manufacturing process monitoring to guarantee product quality.

The problem processing module is to detect and forecast new issues (equipment malfunctions or quality flaws).

These are the five traits of data-driven smart manufacturing:

1. **Centric products** by using user information to create customized products.
2. **Self-organization**, by using task data and manufacturing resources to plan production intelligently.
3. **Self-execution**, by using a range of production process data to achieve accurate control.
4. **Self-learning** and **self-adaptation**, by using current and previous data to perform proactive maintenance and quality assurance.
5. **Self-regulation**, by keeping an eye on the manufacturing process by utilizing real-time status data.

Data-driven smart manufacturing has applications in quality control, manufacturing process monitoring, smart equipment maintenance, smart design, smart planning, and material allocation and tracking.

4. SMART MANUFACTURING SYSTEM

4.1 Design, analysis, and evaluation of smart manufacturing systems

The concepts of manufacturing systems' flexibility and reconfigurability, along with the advancement of their control structures, are becoming increasingly important in the context of the fourth industrial revolution.

The evolution of cyber-physical systems (CPS), their adaptability, and their combined capabilities have made it possible to move from classical manufacturing systems to smart manufacturing systems and from centralized control to heterarchical (decentralized) control architectures [11].

Axiomatic Design Theory (ADT) is used and expanded as a comprehensive methodology for the design, analysis, and evaluation of smart manufacturing systems [12].

Figure 6 shows the three phases in the design of an SMS [13].

A list of Functional Requirements (FRs) is established in **the conception phase**. Performance Metrics (PSs) are grouped to establish a set of performance measures that are prioritized, and accessible virtual and physical assets are taken into account to establish a design space that includes all Design Solutions (DSs).

In **the operation phase,** analysis and design synthesis are done to optimize the system before implementing it in the application.

In the system **reconfiguration phase**, to make the smart manufacturing system sustainable, either specific components or the system as a whole are redesigned.

In order to boost system intelligence in continuous improvement, the suggested technique was used in system development. Prioritized key performance indicators (KPIs) can be used to personalize the system intelligence in a smart manufacturing system.

4.2 Smart Manufacturing Integrated System

A Smart Manufacturing Integrated System (SMIS) is composed of the physical subsystem, the subsystems for information integration, data integration, network integration, and visualization integration.

a) General framework of SMIS

The equipment layer (layer 1), manufacturing line layer (layer 2), workshop layer (layer 3), and enterprise layer (layer 4) make up the physical system. The aspects of information integration, network integration, data integration, and visual integration are used to design it, as shown in Figure 7 [14].

Information integration is the vertical and horizontal integration of information systems between the equipment layer, the production line layer, the workshop layer, and the enterprise layer.

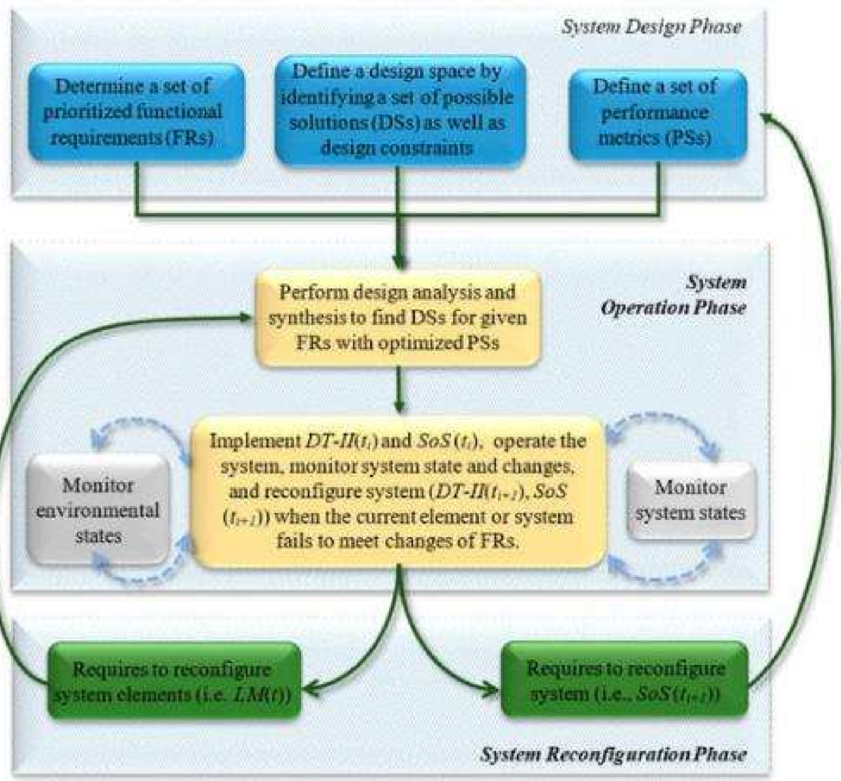

Fig. 6. The design phases of a smart manufacturing system [13]

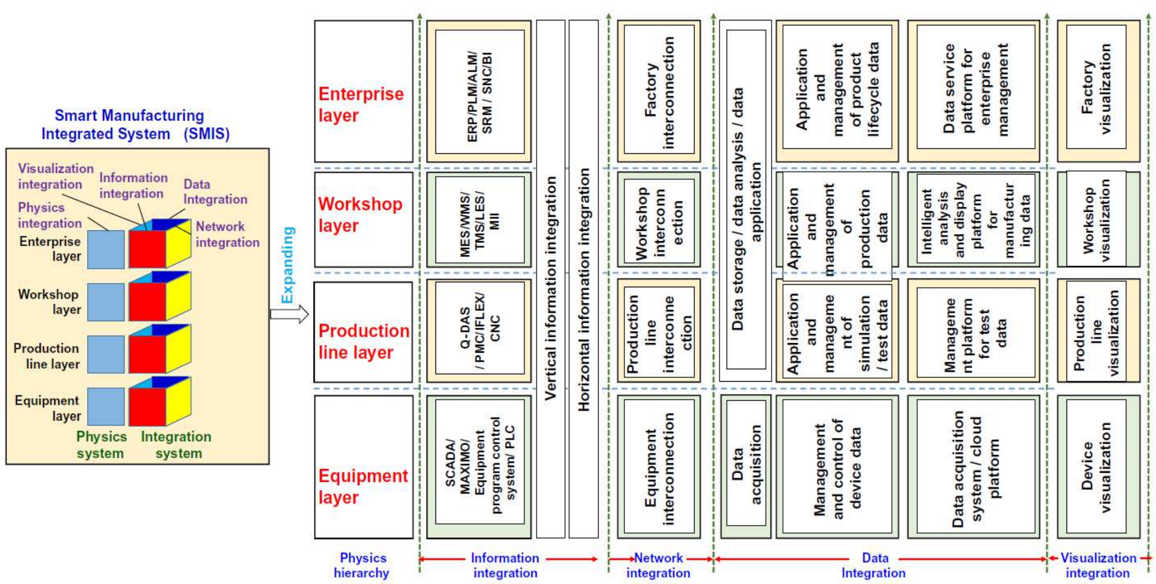

Fig. 7. General framework for SMIS [14].

Network integration is examined from the standpoint of network interconnection, which includes factory, workshop, production line, and equipment connections.

Data integration is analyzed from three dimensions: data processing, data management, and data platform. Data collection, storage, analysis, and application are all included in data processing. Device data management and control, data collection systems, cloud platforms, and other platforms are among the data and platforms that are part of the equipment layer. Simulation and testing data, test data management systems, and other types of data and platforms are utilized at the production line layer. Production data, intelligent analysis platforms, and manufacturing data display platforms are among the platforms and data utilized in the workshop layer. platforms for enterprise management services, product life cycle data, and other platforms.

Visualization integration is constructed at four different levels: factory, shop floor, manufacturing line, and equipment visualization.

The implementation path for SMIS includes 13 steps:

Step 1. The enterprise purchases intelligent equipment, including equipment with intelligent core technology and specific intelligent equipment, such as industrial robots and CNC machines, sensor devices, control devices, testing devices, assembly devices, logistics devices, and storage devices.

Step 2. To get ready for data collection, incorporate sensor systems—such as robot position, torque and tactility sensors, high-performance fiber optic sensors and vision sensors, electronic labels, barcodes, and other acquisition system equipment—into intelligent manufacturing equipment.

Step 3. The SCADA, PLC, and PDU sensor hardware and software systems are part of the existing data acquisition system.

Step 4. Utilize the data acquisition system to gather information from intelligent devices..

Step 5. The configuration of a network integration system includes network connectivity systems at the enterprise, workshop, and equipment levels.

Step 6. Use the network integration system to link every component of the smart manufacturing system.

Step 7. At the equipment, production line, workshop, and enterprise levels, a system for both vertical and horizontal information integration has been built.

Step 8. Create a network integration system and upload the gathered data into the information system.

Step 9. Install a system for data integration and analysis that includes data applications, data storage, and data analysis.

Step 10. Examine and handle the data that has been gathered via the company's IT system.

Step 11. Supply chain management systems, intelligent production cell management systems, intelligent enterprise management platforms, testing and analysis in the digital workshop and production line, equipment control, strategic and tactical management systems, and collaborative management are all examples of operations status analysis.

Step 12. It makes use of the integrated smart manufacturing system. Intelligent loading and unloading at the workshop level, balanced mixed flow production, optimization of processing parameters, real-time production process monitoring, digital logistics tracking, high-precision online monitoring, automatic early warning of equipment failures, and intelligent logistics integration of the workshop are a few examples of intelligent production control and management systems that are applied to the corresponding production activity.

Step 13. The platform's data is shown using a visual integration system, which facilitates accurate and straightforward decision-making.

The organization can use the 13 steps listed above as a reference implementation path for implementing SMIS.

b) General reference architecture of SMIS

Figure 8 depicts the three planes that were the subject of this study, which are made up of the mutual interaction of three dimensions [15].

C1-L (Resource-based Automated Factory), C2-L (Network-based Interconnection Factory), C3-L (Platform-based Data Sharing Factory), and C4-L (Information System Integration Factory) were the four implementation directions for the plan, which was made up of the Smart Characteristics dimension (C) and the Manufacturing System Layer dimension (L).

Using the five system layers—L1 (equipment layer), L2 (process layer), L3 (production line layer), L4 (workshop floor layer), and L5 (enterprise layer)—C1-L was separated into C1-L1 (equipment for core technology and key shortboard), C1-L2 (digital design and simulation), C1-L3 (automatic production line), C1-L4 (digital workshop or factory), and C1-L5 (intelligent management of enterprise).

The plan was defined as C-P (New Model Factory for Product Life Cycle), which consists of the smart characteristics dimension (C) and the product life cycle dimension (P). L-P (New Model Factory for Personalized Customization) was the plan's definition, which consists of the Manufacturing System Layer dimension (L) and the Product life cycle dimension (P).

The implementation of SMIS is divided into six main steps based on the analysis of the SMIS reference architecture.

Step 1, setting up a resource-based automated factory.

Step 2, setting up the network-based interconnection factory.

Step 3, setting up a platform-based data-sharing factory.

Step 4, setting up the information system integration factory.

Step 5, setting up a new factory model for the product life cycle.

Step 6, setting up the new model factory for individual customization.

4.3 Smart Manufacturing System for Mass Personalization

The Smart Manufacturing System for Mass Personalization (S-MMP) is a multidimensional model [16] composed of four dimensions (Fig. 9): the dimension of the evolution process, the dimension of the basic characteristics, the dimension of the industrial value chain, and the dimension of intelligence technology and technique [16].

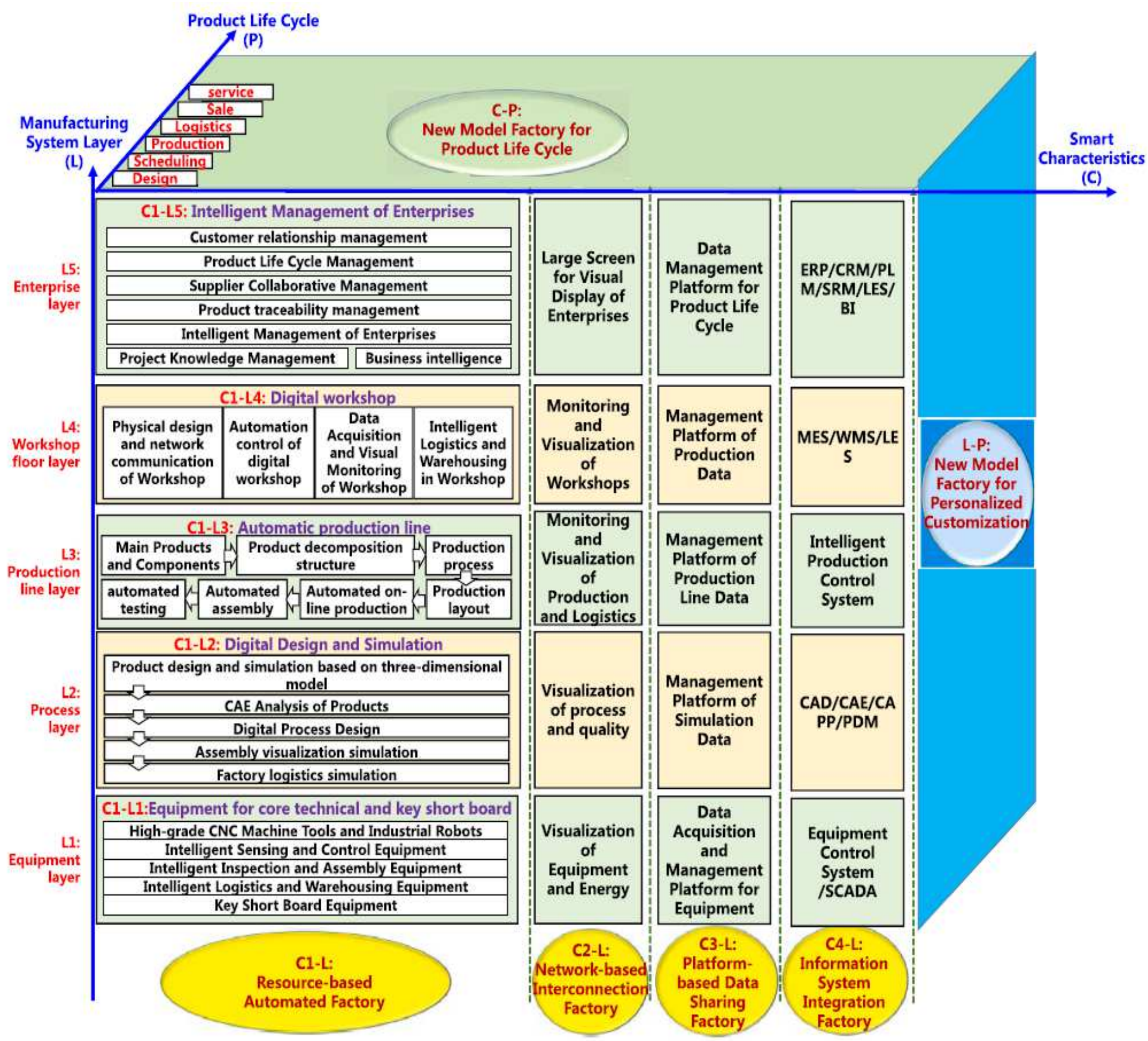

Fig. 8. SMIS reference architecture built on a three-dimensional model [15].

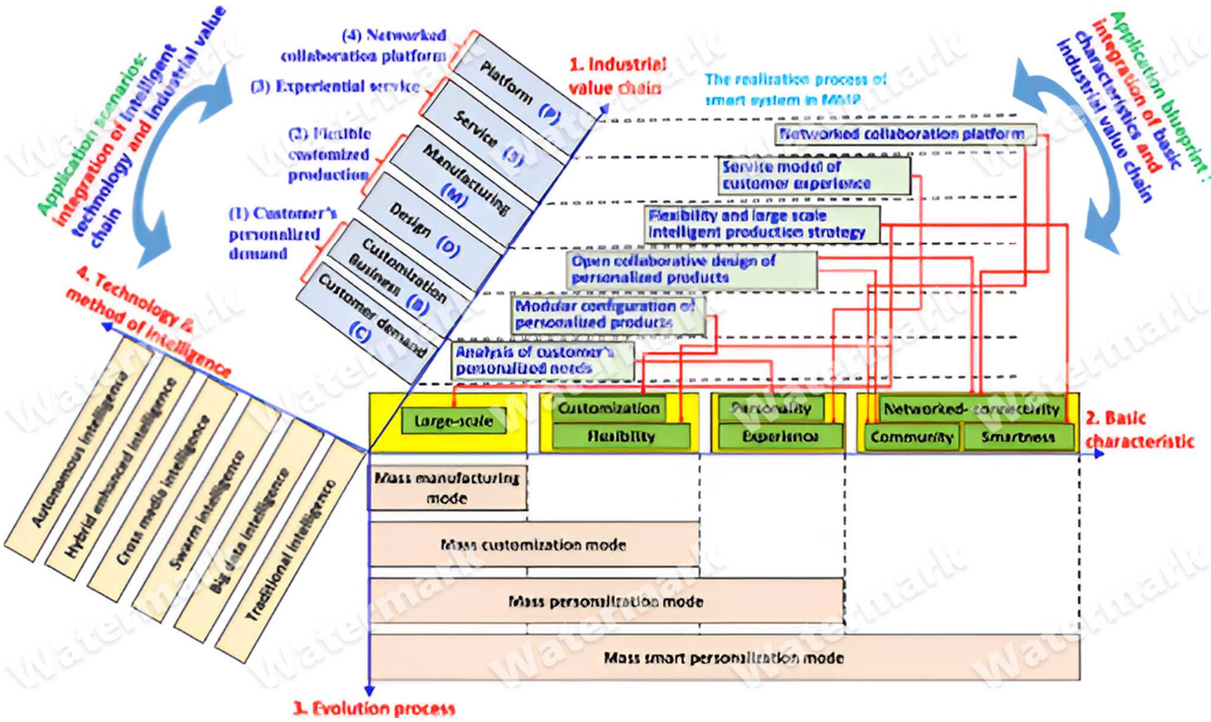

Fig. 9. S-MMP model [16]

Four stages were followed to build the model. First, the process of evolution of the production paradigm is analyzed, which ranges from mass production to mass personalization, mass individualization, and then smart personalization. The main component of the system model is this analytical procedure (industrial value chain dimension).

The S-MMP goal—which encompasses intelligence, community, network connectivity, personality, experience, customization, and scale—arose during the evolution process. The second dimension of the system model is made up of this stuff (the core feature dimension).

The appropriate solutions—that is, clever essential technologies and methods—must be used to accomplish this purpose. The third dimension of the system model is this content (the evolution process dimension).

The precise components, techniques, technologies, models, algorithms, platforms, etc. that must be applied to the industrial value chain process are then applied, and their effects are assessed, by creating application scenarios and application plans. This content is the fourth dimension of the system model (the dimension of technology and intelligence method).

The application model for S-MMP is formed by the cross-integration of the first and second dimensions. The application scenario for S-MMP is formed by the cross-integration of the first and fourth dimensions.

The implementation of S-MMP is divided into six steps: smart tool development, smart technology development, smart function design, smart feature activation, smart application scenario planning, and extending intelligence to the industry.

4. EVOLUTION AND FUTURE OF MANUFACTURING, RESEARCH PERSPECTIVES

According to Universal Robots CTO, Industry 5.0 is the "human touch" revolution because it turns widespread personalization—made possible by Industry 4.0 technologies—into mass individualization. Additionally, he predicts a return to the pre-industrial method of production, which is facilitated by technology that depends heavily on humans [5].

Manufacturing has witnessed substantial changes over many decades, impacted by the items created, the technologies used, and the business tactics employed (Fig. 10).

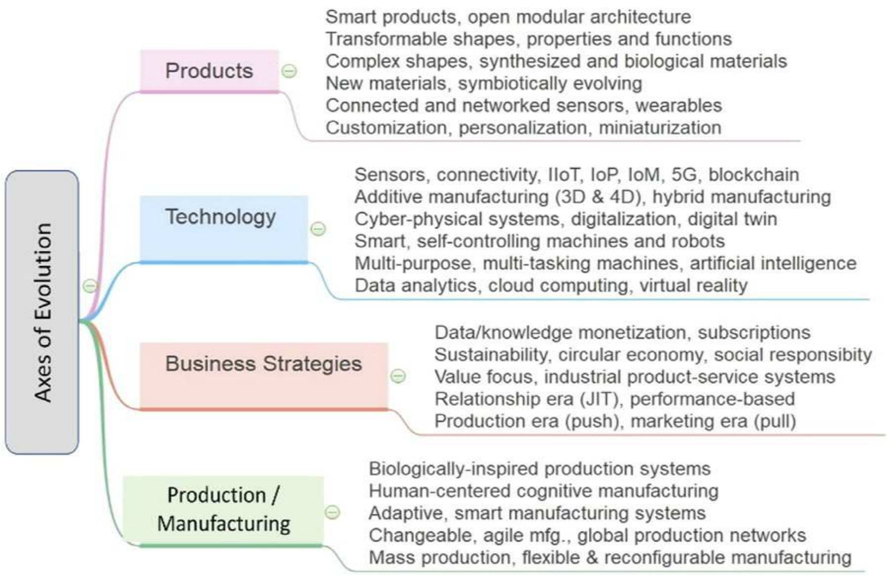

Fig. 10. The four axes of evolution [17].

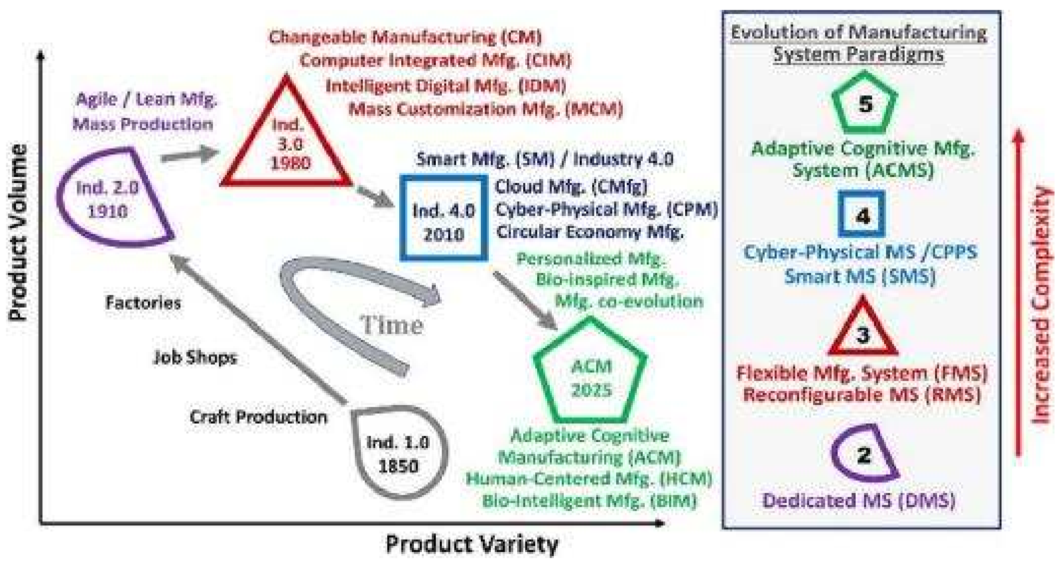

Fig. 11. Manufacturing paradigms and manufacturing systems paradigms [17].

The design, configuration, operation, and control of manufacturing systems are constantly evolving in an ecosystem with ever-more complex components, disruptive technologies, and business models.

Their future will be shaped by commercial tactics and socio-technical advancements [17].

Figure 11 illustrates how the manufacturing systems paradigm has changed as a result of modifications to goods, production technology and procedures, production volume, and differing levels of automation, intelligence, and adaptation [17].

The evolution of manufacturing across industrial revolutions—from artisanal production to the current era of intelligent manufacturing and into the future of bio-intelligent manufacturing—is examined in relation to the development of manufacturing systems and emerging trends toward cognitive smart manufacturing.

By utilizing Industry 4.0 and 5.0 technologies, such as Artificial Intelligence and Big Data Analytics, Adaptive Cognitive Manufacturing (ACM) produces actionable insights and human-machine interactions.

All will be enabled and supported by AI modules, smart sensors, extensive information and data analytics, automated, cognitive, and hybrid human-machine adaptive actions, and execution methods, as well as human experience and wisdom.

The paradigm of Adaptive Cognitive Manufacturing (ACM) will gain more industry adoption and become more transparent, human-centric, adaptive, and predictive.

In conclusion, as manufacturing progresses to the next level, the Adaptive Cognitive Manufacturing System (ACMS), there will be major technological challenges. New research directions are needed to aid in the creation of future industrial systems, through:

- Their cognitive and digital changes, including how manufacturing processes are supported physically, perceptually, and cognitively;
- Techniques for static, dynamic, cognitive, and extreme adaptation;
- Adaptability, reactivity, flexibility, reconfiguration, and modularity;
- Knowledge-intensive, cyber-physical, biologically inspired, intelligent, and cognitive manufacturing systems;
- Improved autonomous systems that are networked, integrated, and connected.

The next generation of intelligent devices, systems, and enterprises will be characterized by fully integrated and intrinsically intelligent systems, subsystems, and components.

5. CONCLUSION

Some conclusions for this paper:

1. The transition from Industry 4.0 to Industry 5.0 marks a shift from automated and data-driven systems to human-centered and sustainable manufacturing processes.
2. Industry 5.0 emphasizes the reintegration of human collaboration, advancing beyond the digital connectivity of Industry 4.0.
3. This shift enables mass personalization to evolve into smarter and more predictive personalization, where customer involvement and data play critical roles.
4. The adoption of technologies like AI, smart sensors, blockchain, and digital twins facilitates the creation of adaptive cognitive manufacturing systems.
5. Future research and development should continue to explore the integration of these technologies to further improve manufacturing systems and address emerging challenges.

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Fabricația în Industria 4.0 către Industria 5.0

Lucrarea examinează tranziția de la Industria 4.0 la Industria 5.0, concentrându-se pe transformările semnificative în producție. În timp ce Industry 4.0 pune accent pe conectivitate digitală, automatizare și personalizare inteligentă bazată pe date, Industry 5.0 reintroduce colaborarea umană și practicile durabile, având ca scop sisteme de fabricație cognitivă adaptive. Această nouă paradigmă folosește tehnologii avansate precum AI, senzori inteligenți, blockchain și gemeni digitali pentru a îmbunătăți eficiența, inovația și abordările centrate pe om. Articolul conturează evoluția paradigmelor de producție, trecând de la producția de masă la personalizarea în masă, condusă de big data și sisteme inteligente. De asemenea, evidențiază dezvoltarea sistemelor de fabricație inteligente, inclusiv integrarea instrumentelor inteligente, monitorizarea în timp real și cadrele de analiză a datelor, alături de pași pentru implementarea proceselor de producție durabile, personalizate și flexibile.

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