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Overview of Manufacturing Systems—Evolution from Group Technology to Dynamic Cellular Manufacturing System

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Abstract

In the face of a tumultuous economic landscape and the swift progress of technology, businesses find themselves compelled to reshape their economic strategies in response to the challenges posed by intense global competition. Numerous scholars have delved into the realm of manufacturing systems and its array of tools. This study conducts a thorough examination of the transition from Group Technology to Dynamic Cellular Manufacturing System and offers insights into the future of manufacturing systems, particularly the application of industry 4.0 in asset management.

Keywords

Manufacturing Systems, Group Technology, Dynamic Cellular Manufacturing System, Industry 4.0, Asset Management

1. Introduction

In this section, we highlight key attributes of manufacturing systems, including Fixed Automation Systems (FAS), Flexible Manufacturing Systems (FMS), and Single-Stage Multi-Machine Systems (SSMS). The ultimate aim of this review is to aid decision-makers in selecting the most suitable facility layout among FAS, FMS, or SSMS.

A manufacturing system comprises machines, transportation means, computers, storage buffers, personnel, and other components assembled to produce products (Gershwin, 2002). Typically, it includes multiple interconnected workstations, often referred to as cells or work centers. Manufacturing industries confront various challenges and constraints, including economic globalization marked by increased economic interdependence and technological advancements, escalating international competition, and the globalization of markets. Actors in this sector are compelled to adjust their economic models to address the challenges posed by intense competition in international economies.

The manufacturing environment plays a pivotal role in shaping the performance of a manufacturing system. The decline of Mass Production (MP) in the United States led to the emergence of various approaches better suited for the rapid changes in manufacturing during the 1980s (Duguay et al., 1997). MP systems were solely focused on reducing product costs (Mehrabi et al., 2000). Today, the manufacturing environment is not just stochastic; it is characterized by uncertainty. To address this insecurity, new manufacturing system concepts are emerging as viable alternatives to conventional production systems. Over the years, several production systems have been proposed, including Mass Production Systems, Lean Production, Agile Production, Custom Mass Production, Flexible Manufacturing Systems (FMS), Dynamic Cellular Manufacturing System (DCMS), and Reconfigurable Manufacturing Systems (RMS).

The survival of industries involved in these systems hinges on the achievement of their ultimate goals: gaining value in the form of profit, reputation, and market share. There is a growing realization that the enduring competitive advantage in the global economy lies in developing the capability to swiftly respond to the demand for customized, high-quality manufacturing products (Molina et al., 2005). Consequently, manufacturers are progressively adopting production systems capable of delivering high-quality products at reduced costs, all while adhering to manufacturing and delivery deadlines.

The paper delves into the evolution of manufacturing systems, specifically from Group Technology to Dynamic Cellular Manufacturing Systems. This study is crucial in understanding how manufacturing has adapted and will continue to evolve in response to global economic challenges and technological advancements. It provides valuable insights into the integration of modern technologies like industry 4.0 into manufacturing processes. Such an understanding is essential for stakeholders in manufacturing and related industries to stay competitive and innovative in a rapidly changing economic landscape. However, the article may have limitations related to the scope of systems reviewed.

The research is structured as follows: section II introduces the concept of Fixed Automation Systems; section III covers the Flexible Manufacturing System. Section IV delves into Single-Stage Multi-Machine Systems, while section V explores the concepts of Dynamic Cellular Manufacturing System and Reconfigurable Manufacturing System. Section VI looks into the future of manufacturing systems, particularly Industry 4.0. Lastly, section VII provides the concluding remarks for this review.

2. Fixed Automation Systems

This section focuses on the key characteristics of a specific conventional production system, namely Fixed Automation Systems (FAS) in the form of Automatic Transfer Lines (ATLs), also known as Automatic Production Lines (APL). In scientific literature, Automated Manufacturing Systems (AMS), such as transfer lines, can be defined in various ways. A production line is essentially a sequence of workstations where each workpiece undergoes a specific operation as it moves from one station to the next (Buzacott, 1967; Groover, 2020). ATLs, as defined by Gershwin (2002), are a linear network of service stations or machines (M_1, M_2, …, M_k) interspersed with buffer storages (B_1, B_2, …, B_{k-1}). Machine behaviors are not entirely predictable; they are susceptible to random failure and maintenance, and can be in operating, idle, or broken states, potentially disrupting neighboring machine operations. Therefore, buffer storages are essential to mitigate such potential disruptions. **Figure 1** illustrates an ATL.

The machine sequences in ATLs are predetermined and controlled by an automated support system designed for manufacturing a very limited family of parts. However, a common challenge in justifying the utility of ATLs lies in the lower efficiency of the line, resulting from the arrangement of stations to form the line, compared to the use of individual machines. This issue stands as a significant challenge for ATLs, as a blockage at one station can halt the entire line. To address this, dividing the line into stages and incorporating buffer stores between the stages can enhance ATL efficiency (Buzacott, 1967). It is worth noting, however, that buffer storages come with a cost to the company as they occupy valuable space. Buzacott (1982) applies dynamic programming to assess operating rules for Automated Manufacturing Systems (AMS), specifically a two-stage transfer line prone to failure. Control policies involve decisions on machine operation and technician dispatch for corrective maintenance, with system states defined by machine failures/repairs and buffer sizes. While AMS offers potential for improved control policies, Buzacott (1982) highlights the challenge of formulating and solving satisfactory models for AMS control policies and operations. The complexity of Automatic Transfer Lines (ATL) arises from stochastic failures, multilevel control needs, job routing and processing time requirements, and information collection challenges.

3. Flexible Manufacturing Systems

A Flexible Manufacturing System (FMS) is a production system designed for adaptability, capable of responding to anticipated and unexpected changes. The concept of flexibility in manufacturing is multifaceted and broad (Sethi & Sethi, 1990; Diop et al., 2019). FMS functions as an automated group technology cell with interconnected processing stations controlled by a computer (Groover, 2020;

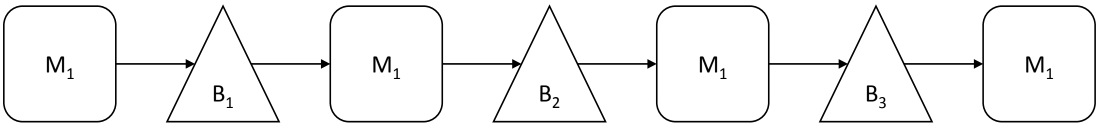

Figure 1. Four-machine transfer line (source: Gershwin, 2002).

Stecke, 1983). FMSs go beyond Computer Numerical Control (CNC) systems, incorporating support equipment like Material Handling Systems (MHSs), Automated Guided Vehicles (AGVs), and Automatic Storage and Retrieval Systems (AS & RS) (Diop et al., 2019; Raj et al., 2008). FMS consists of three main elements: Processing Equipment, Material Handling Equipment, and Computer Control Equipment (Tompkins et al., 2010). The term FMS emphasizes both the extent of automation and part diversity. Notably, systems with only automated material handling, fixed transfer lines, or those lacking integrated CNC machines do not meet FMS criteria. Achieving flexibility in FMS involves standardized handling and storage components, independent production units, a flexible material-delivery system, centralized Work-In-Process Storage (WIPS), and a high degree of control. It is crucial to recognize that CNC exclusively controls operations at machines, MHSs, and AGVs (Tompkins et al., 2010; Gershwin, 2002; Browne et al., 1984).

To qualify as flexible, an Automated Manufacturing System (AMS) must exhibit features such as processing different part styles in a non-batch mode, adapting to schedule changes, gracefully handling equipment breakdowns, and accommodating the introduction of new part styles (Groover, 2020; Diop et al., 2019). FMSs enable the production of a diverse range of manufactured goods on a single system, as highlighted by Mehrabi et al. (2000). These systems possess the unique capability of rapid adaptability to production, maintenance, and safety constraints. FMSs are highly automated production systems well-suited for manufacturing different product series and various product lines. This adaptability empowers decision-makers to address the challenges posed by the stochastic and uncertain environment inherent in these systems. The justification for flexibility in a production system arises from the need to navigate both internal and external environmental uncertainties, as noted by Koo (1996).

Setting up or changing tooling for a machine, transitioning from producing one product type to another, typically involves time and cost. When the setup cost is zero, the machine or system is considered flexible, as per Gershwin (2002). Flexibility in this context signifies the system's capacity to perform more than one task, providing options or choices in an FMS. This adaptability is tied to the system's ability to manufacture at least two different types of parts within a specified period (Product Flexibility) or to produce the same part using different configurations (Process Flexibility or Multiple Road). Compared to traditional batch operations, FMS technology, as noted by Groover (2020), offers advantages such as reducing production lead times, increasing system utilization, lowering work-in-progress (WIP), and enhancing scheduling flexibility. The design of these production systems aims to achieve efficiency levels equivalent to a well-balanced Transfer Line and the flexibility of a Job-shop capable of producing multiple part types concurrently (Raj et al., 2008; Browne et al., 1984; Stecke, 1983). Job shops, known for their adaptability to variations in production operations and diverse products, seek to minimize production time and cost.

Upon reviewing the literature, it becomes evident that various definitions and uncertainties exist regarding the conditions that warrant labeling a production system as an FMS. This contributes to confusion surrounding the concept. To dispel ambiguity, eight distinct types of flexibilities in manufacturing are identified: 1) machine flexibility, 2) process flexibility, 3) product flexibility, 4) routing flexibility, 5) volume flexibility, 6) expansion flexibility, 7) operation flexibility, and 8) production flexibility. These flexibilities are defined in **Table 1** provided below. As far as we know, there isn't a universally accepted standard definition for the term FMS, with most definitions focusing on the system's hardware

Table 1. Eight common types of flexibilities (source: adapted from Browne et al., 1984).

#	Types of flexibilities	Descriptions
i	Machine Flexibility	When both the machine and the sequence of operations can be reconfigured to accommodate the changes required for producing a variety of product types or specific components. This encompasses product flexibility, process flexibility, and operation flexibility.
ii	Process Flexibility	It denotes the process's ability to adjust to diverse manufacturing contexts and requirements. This flexibility represents the capability to manufacture a specific set of part types, each potentially utilizing different materials, through various methods.
iii	Product flexibility	It refers to the system's ability to switch from producing one set of products efficiently and swiftly to another. It is all about adapting to changes in demand and maintaining cost-effectiveness.
iv	Routing Flexibility	When a manufacturing system possesses the flexibility to execute the same manufacturing operation using different machines and adapt to fluctuations in production capacity, such as an increase in the number of units to be manufactured. This flexibility is characterized by the ability to utilize alternative routes, involving alternative machines, operation sequences, or methods (volume flexibility and expansion flexibility). Chan (2001) defined it as the capability to manage breakdowns and continue producing the specified set of part types.
v	Volume flexibility	When the manufacturing system can be operated economically across various production volumes due to factors like increased automation, multipurpose machines, routing flexibility, and similar features.
vi	Expansion flexibility	The capability to expand the FMS effortlessly as needed. This can be accomplished through elements such as a non-dedicated, non-process-driven layout, a flexible materials handling system using wire-guided carts, and modular, flexible machining cells with pallet changers, along with routing flexibility.
vii	Operation flexibility	It refers to the system's capability to change the order of operations for different part types. It allows for adaptability in the manufacturing process, accommodating variations in production requirements without significant reprogramming or reconfiguration. This flexibility is essential for efficiently handling diverse production needs in a dynamic manufacturing environment.
viii	Production Flexibility	It refers to the range of part types that an FMS can produce, dependent on the current technological capabilities. This concept encompasses the variety of production alternatives associated with a product and is closely tied to process flexibility and routing flexibility. Part flexibility contributes to resource dependability, especially when dealing with unpredictable resources. It can be categorized into two main types, each with several subcategories: Machine Flexibility (MF) and Routing Flexibility (RF). MF involves the FMS's capability to utilize different machines to perform the same operation on a product and adapt to significant changes, such as in capacity, volume, or capability. RF pertains to the FMS's ability to modify for producing different part types and alter the sequence of operations performed on a product.

composition. The degree of automation plays a crucial role in determining the flexibility level of an FMS. Flexibility, in this context, refers to the system's ability to produce multiple parts with minimal cost and time loss during machine configuration changes (setup). This particular characteristic distinguishes FMS from other manufacturing systems and necessitates investments in flexible machines, equipment changers, and versatile operators. However, implementing these flexible systems involves substantial costs, emphasizing the importance of making a long-term investment considering the volatile economic context. The operational approach and the degree of flexibility are pivotal factors in decision-making (Browne et al., 1984). Therefore, careful consideration is required to determine the optimal degree of flexibility that balances implementation costs with the benefits offered by the FMS.

4. Single-Stage Multi-Machine Systems

The concept of Single-Stage Multi-machine Systems (SSMS) has emerged in response to the evolving manufacturing landscape, particularly driven by mass customization. This type of manufacturing system is defined by Build to Order (BTO) practices, also known as Make to Order (MTO) or Made to Order (MTO), characterized by unpredictable customer demand, a wide product variety, a tool flow strategy, and a no-routing approach (meaning products should not be transferred between workstations) (Chung & Koo, 1991). SSMS serves as an automation alternative in machining systems and can be viewed as a specialized form of a FMS with multiple cells, each operating only one machine. It can also be conceptualized as a collection of autonomous Flexible Machining Modules (FMM) (Chung & Koo, 1991). It is characterized by various associated resources, including 1) Manufacturing Configuration and Machines, 2) Parts, 3) Tools, 4) Part Transporters, and 5) Tool Carriers (Tompkins et al., 2010; Chung & Koo, 1991).

In the context of *Manufacturing configuration and machines* in SSMS, the similarity and versatility of machines within machining centers allow any given machine to perform all operations on a specific product type. Once a machine begins working on a product, the product remains on that machine until all necessary operations are finished. Each machine possesses its own tool magazine, fully supplied by the Tool-Delivery System (TDS), which serves as a critical resource. Two alternative TDSs in an SSMS are illustrated in **Figure 2** and **Figure 3**.

Parts in the SSMS, products enter the system based on the specifications outlined in the production schedule. The manufacturing operations for a product are exclusively conducted by a single machine, and it is essential to note that all machines are identical, as mentioned earlier. Once a machine initiates the production process for a product, the product remains on that machine until all necessary operations are concluded. The flow of products within the system is facilitated by a transporter system.

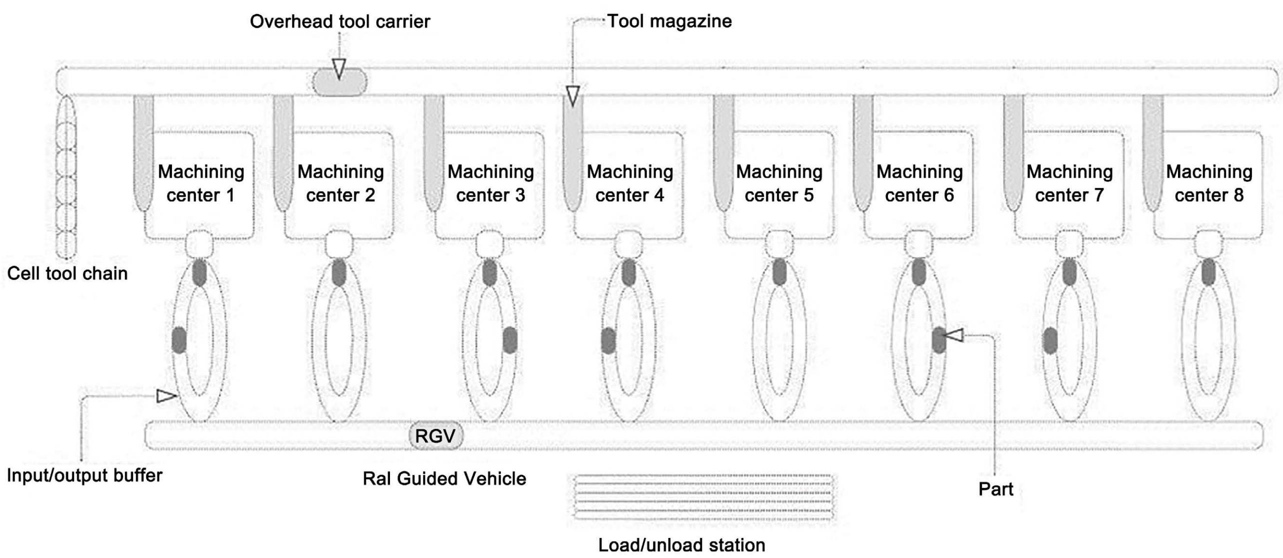

Figure 2. SSMS with a centralized tool storage (source: Own representation based on Koo, 1996).

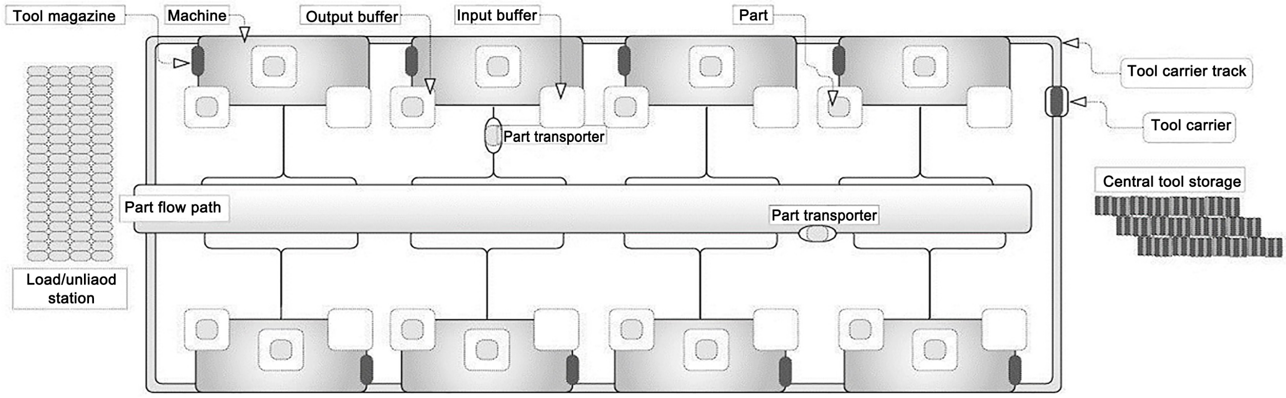

Figure 3. SSMS with distributed tool storage (source: Own representation based on Koo, 1996).

Tool management poses a challenge in a dynamic tool-sharing environment when coordinating operations across multiple machines. The process planning plays a crucial role in establishing the sequence of operations, including specifying the required tools, before the actual manufacturing of the product takes place.

The role of *Part Transporters* is minimal due to the nature of the system where all operations on a given product are conducted by a single machine. Consequently, the product makes only one visit to the designated machine.

Tool Carriers are responsible for transporting tools from centralized tool storage to a designated machine. An illustration of a joint schedule involving machines and tools in SSMS is depicted in **Figure 4**.

A new era of manufacturing systems, termed Dynamic Cellular Manufacturing System (DCMS) or Reconfigurable Manufacturing Systems (RMS), has recently emerged. Molina et al. (2005) argue that the next generation of manufacturing systems needs to surpass the flexibility of past decades. These systems

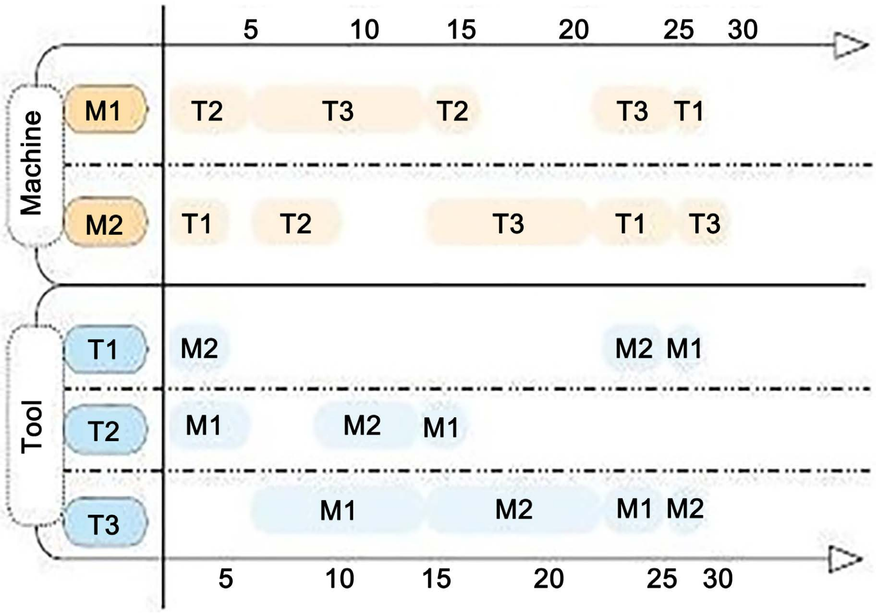

Figure 4. A joint schedule of machines and tools (source: Own representation based on Koo, 1996).

must be swiftly reconfigurable and possess sufficient intelligence to align with the demands of a highly dynamic market. However, the introduction of modern technologies to adapt to this new industrial reality comes with exceptionally high costs.

5. Dynamic Cellular Manufacturing System

This section focuses on the key characteristics of the Dynamic Cellular Manufacturing System (DCMS), also acknowledged as Reconfigurable Manufacturing System (RMS). To provide context, a brief overview will be presented on certain attributes of a conventional production system known as the Cellular Manufacturing System (CMS), which serves as a foundation for building a DCMS or RMS.

CMS is a production process that falls within the realms of Lean Manufacturing (LM) and Just-In-Time (JIT) manufacturing, incorporating Group Technology (GT) principles (Groover, 2020). GT is a holistic approach that involves identifying and leveraging similarities among parts in design and manufacturing. In CMS, the focus is on manufacturing a set of similar products, known as part families, utilizing a Group Technology Machine cell. This machine cell comprises various types of machines, including those with manual handling, mechanized handling, flexible manufacturing cells, and FMS (Groover, 2020). The production flow in CMS involves the product transitioning from one cell to the next, which houses one or more distinct machines, each responsible for specific tasks in the production process. Notably, in CMS, a majority of the machines are automatic, and changeovers can be swiftly executed, contributing to its flexibility, and yielding significant advantages.

Over the course of history, the evolution of production systems has been driven by customer demands and the dynamic nature of the market, transitioning from mass production to the advent of flexible and reconfigurable systems. In the early 20th century, mass production played a pivotal role in shaping a new social class by providing employment opportunities and means of production, ultimately enhancing the quality of life for this segment of society (Molina et al., 2005).

However, in the latter half of the century, these manufacturing systems faced challenges in terms of efficiency and effectiveness in meeting the escalating demands of increasingly discerning customers. This led to the emergence of Next Generation Manufacturing (NGM), necessitating the incorporation of new concepts. Manufacturing industries in the 21st century must embrace the principles of flexibility and agility outlined by NGM to attain operational excellence and sustain competitiveness (Duguay et al., 1997). Molina et al. (2005) highlight the derived concept from the NGM mission, namely RMS, designed to accommodate to the diverse demands for various products. They emphasize that NGMs must integrate increased flexibility and intelligence to progress towards RMS. The authors argue that the significance of intelligence in this context arises from the imperative to maintain more efficient and effective manufacturing operations, minimizing downtime in the face of uncertainty.

RMS integrate hardware and control resources across all levels of functionality and organization. This enables swift adjustments in capacity and functionality to respond promptly to sudden shifts in economic markets or changes in regulatory requirements (Bi et al., 2008). However, differences in defining this type of production system emerged during the third conference on RMS at the University of Michigan in May 2005. Participants were divided into categories: some view RMS as an intermediary paradigm between Mass Production Systems and FMS, others argue that RMS represents an advanced manufacturing system with higher flexibility than FMS, and a third category sees no distinction between FMS and RMS.

6. The Future of Manufacturing Systems: Industry 4.0

The landscape of industrial systems is undergoing substantial transformation due to innovations in cost-effective technologies, widespread sensor deployment, rapid computational capabilities, and the integration of artificial intelligence for efficient data analysis (Gershwin, 2018; Diop et al., 2021). This section delves into the concept of Industry 4.0 and its diverse array of tools.

Across diverse sectors, the significance of integrated risk management is on the rise. Asset managers, dealing with a plethora of complex and uncertain technological objects stemming from Industry 4.0, must navigate infrastructures and decision-making processes. Furthermore, organizations are confronted with dependability challenges (Reliability, Availability, Maintainability, and Safety—R-AMS) in the era of digitalization in industrial production systems. In response to this situation, Asset Management (AM) emerges as a research focal point of significant interest in the scientific community. There is an increasing focus on addressing the challenges posed by the myriad of new technologies associated with Industry 4.0, including the Internet of Things (IoT), Cyber-Physical Systems (CPS), Cloud Computing, Cognitive Computing (CC), artificial intelligence, and big data.

1) *Emergence and Origins of Industry 4.0*

The term Industry 4.0 was coined to signify the fourth industrial revolution, emphasizing automation, digitization, device connectivity, information sharing, and data security to optimize production capacity (Diop et al., 2021, 2019; Blanchet & Bergerried, 2014). This represents a digital transformation that profoundly impacts manufacturing and production processes across various industries, marking the fourth revolution propelled by the Internet and the IoT. Originating from a German initiative aimed at enhancing the competitiveness and productivity of the manufacturing sector, the concept emerged in 2006 with the presentation of the German government's High-Tech Strategy at the Hanover Fair, the world's largest industrial technology fair. The term Industry 4.0 was first associated with the notion of an industrial revolution during this initiative. In 2011, at the same Hanover Fair, a collaborative effort by representatives from business, politics, and science, including Dr. Kagermann, Dr. Wolfgang Wahlster from the German Research Center for Artificial Intelligence, and Dr. Wolf-Dieter Lukas from the Federal Ministry of Research and Education, presented the outcomes of their work on Industry 4.0. Their publication outlined three main axes shaping the characteristics of future industrial manufacturing engineering: a high degree of product customization with flexible production, active involvement of customers and business partners in design and value creation processes, and the integration of production and quality services to generate hybrid products (Kagermann et al., 2011).

The perspective on the industry has undergone rapid global evolution, culminating in the fourth industrial revolution, commonly referred to as Industry 4.0 or the industry of the future. This revolution introduces a novel approach to organizing and controlling the industry value chain through intelligent networking of machines and processes. Industry 4.0 establishes a connection between the virtual and real worlds, facilitated by the industry 4.0 platform. Key elements of this transformation include automation, the exchange of massive data (Big Data), and the integration of ubiquitous computing solutions in manufacturing technologies, such as the IoT, CPS, Cloud Computing, and Cognitive Computing (Erboz, 2017). The emergence of the Smart Factory stands out as a defining feature of Industry 4.0, signaling a digital transformation in manufacturing and the connected value creation activities and processes. At the core of Industry 4.0 are CPS, exemplified by smart machines. These advanced control systems are distinguished by their connectivity through the IoT, incorporating Embedded Software Systems and possessing Internet Protocol (IP) addresses for seamless communication with other systems. Digital transformation, marked by the interconnection and synchronization of systems through new technologies, differs fundamentally from the digital divides that characterized the three previous revolutions: mechanization of production through the steam engine, mass production and the advent of the assembly line through electricity in the early 20th century, and the automation of production through information technology and electronics in the 1970s.

2) *Industry 4.0 Technologies*

The advent of Industry 4.0 affects all industrial spheres and integrates new modern and advanced technologies. These technologies capture, optimize and deploy big data. We are witnessing the emergence of the Smart Factory concept, which is an important link in Industry 4.0. Technologies such as Industrial Internet of Things (IIoT), Artificial Intelligence (AI), CPS and Cloud Computing (On-Demand Availability of Computer System Resources) communicate, interact, and adapt continuously (Boston-Consulting-Group, 2020). The IoT is reshaping decision-making processes in product design and manufacturing, with global estimates projecting 50 to 200 billion connected objects by 2020, surpassing the number of cellphones (European-Asset-Management-Committee, 2017). Furthermore, the International Data Corporation (IDC) anticipates a significant increase in global spending on IoT, reaching from 656 billion to 1.7 trillion dollars between 2014 and 2020, fostering the growth of digital devices and solutions.

Industry 4.0 involves the integration of various modern technologies to create value, encompassing four key digital components: CPS, IoT, Cloud Computing, and Cognitive Computing (CC).

CPS is a computer system in which a mechanism is controlled or monitored by computer algorithms, creating a close interaction between cyber and physical components (Bartodziej & Bartodziej, 2017). CPS integrates software and hardware, functioning across different spatiotemporal scales and adapting to context changes (Khaitan & McCalley, 2014). This convergence of the Physical and Digital Worlds establishes global networks for integrating manufacturing systems, machines, and warehousing systems (Shafiq et al., 2015; Wang et al., 2016). CPS examples include smart grids, industrial control systems, robotic systems, airplane autopilots, self-driving cars, and medical surveillance. These systems utilize microcontrollers, sensors, and actuators to exchange information through on-board computer terminals, wireless applications, or clouds, evolving through generations of technologies (Lu, 2017). CPS systems have undergone three technological generations (Wang et al., 2016): the initial generation utilized technologies like RFID for unique object identification through bar codes, coupled with centralized data management (storage and analysis); the second generation featured technologies incorporating sensors and actuators with a restricted set of functions; the third generation embraced technologies with networked sensors and actuators capable of both storing and analyzing data. Strang et al. (2016) delved into the dynamic and adaptive allocation of workers and the incorporation of human factors into Cyber-Physical Production Systems (CPPS). Their approach involves deciding on worker allocation based on information gathered about the human operator and the CPPS, as well as fostering communication among different entities within the system. The assignment of a human operator to a station occurs only if the individual possesses all the necessary characteristics from both a personal and professional standpoint. Therefore, the effectiveness of integrating human factors into a CPPS heavily relies on the satisfaction and profile of the human operator, aiming to optimize the overall productivity of the system. Additionally, it is noteworthy that a virtual mock-up (Digital Mock-up or DMU) of the physical world can be crafted using cyber-physics to control physical processes (Erboz, 2017). Virtualization entails creating a digital replica of the physical world, enabling the CPS to exert control over the physical processes within the plant (Wang, 2016).

The IoT refers to the network of interconnected technological physical objects, incorporating sensors and software. These objects are designed to connect and exchange data with other systems through the internet (Erboz, 2017; Wang, 2016). According to the International Telecommunications Union (ITU), the IoT is defined as a global infrastructure for the information society. It enables advanced services by interconnecting both physical and virtual things using existing and evolving interoperable information and communication technologies (Rec. ITU-T Y.2060 (06/2012)). IoT systems rely on cloud computing infrastructures and CPS. In essence, IoT represents a system comprising interconnected computing devices, mechanical and digital machines, objects, humans, or animals, each with Unique Identifiers (UIDs). These entities have the ability to transfer data over a network without requiring direct human interaction (H2H Human-to-Human interaction or H2C Human-to-Computer interaction) (Rouse, 2020). It is essential to note that the term "object" refers to entities associated with information, whether static or dynamic, that can be identified and integrated into communication networks of the physical world or information networks (ITU-T-Y.4000, 2016). Virtual objects are information entities processed and accessible through software packages and computer programs, while physical objects, such as electrical equipment and industrial robots, exist in the tangible world and can be connected and controlled. In the context of the IoT, it encompasses software application programs for process control, real-time data collection from remote sites, and serves as an extension of Supervisory Control and Data Acquisition (SCADA). SCADA integrates hardware components that collect and feed data into a computer with installed SCADA software for processing and timely presentation (Rouse, 2020). Flexible Manufacturing Systems (FMS) and Reconfigurable Manufacturing Systems (RMS) are incorporating intelligence, enabling communication between machines (Machine to Machine, M2M), the system, and the human operator (Machine to Human, M2H/System to System, S2S). M2M involves connecting a device to the cloud (Cloud), managing it, and collecting data (Rouse, 2020). The evolution of IoT from M2M communication, where machines connect without human interaction, underscores its success in acquiring and identifying data while ensuring confidentiality and security (ITU-T-Y.4000, 2016). IoT's strength lies in its capacity to establish communication not only anywhere and anytime but also with any object.

Cloud computing, defined as the on-demand availability of computer system resources, enables users to access computer services through a provider's cloud. The cloud primarily encompasses computing power and storage without direct user administration (Mell & Grance, 2011; Montazerolghaem et al., 2020). Cloud computing providers offer three standard service models: Software-as-a-Service (SaaS) for applications like management software, ERP, CRM, email, etc., where consumers use applications on the provider's cloud infrastructure; Platform-as-a-Service (PaaS) for accessing cloud applications, with consumers managing the implemented applications while the provider controls the infrastructure; Infrastructure-as-a-Service (IaaS) for data storage, virtual machines, servers, networks, and essential computing resources, where consumers can install and run software, managing applications and operating systems, while the cloud infrastructure is controlled by the provider (Mell & Grance, 2011). **Figure 5** illustrates these three standard service models of cloud computing solutions. Highlighting major players in the on-demand availability of IT system resources (Haug et al., 2016), notable market giants include: 1) Amazon Web Services (AWS), offering platforms and APIs on a pay-per-use basis; 2) Google, known for Google Drive; 3) Microsoft, featuring Windows Azure; and 4) IBM, recognized for Blue-Cloud.

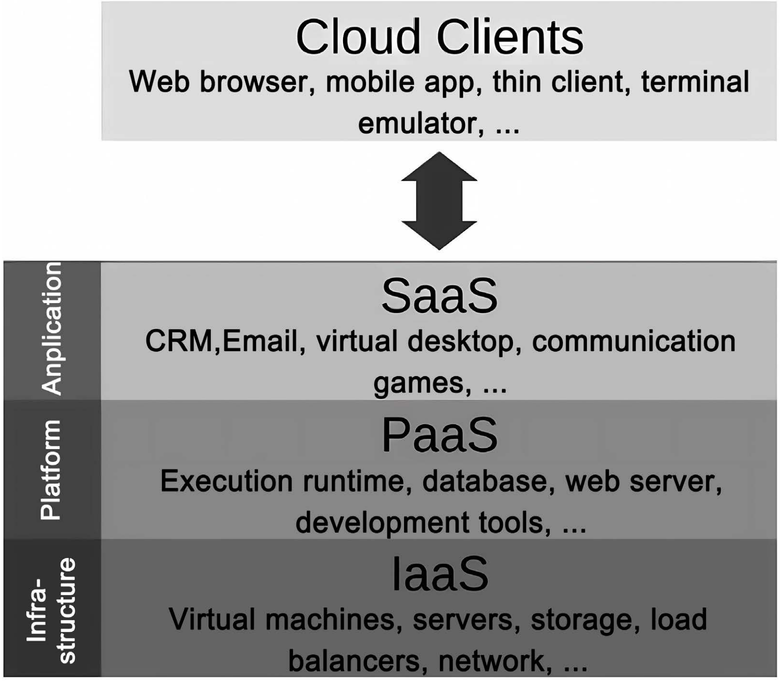

Figure 5. Cloud computing service models portrayed as layers in a stack (source: Mell & Grance, 2011).

Cognitive Computing (CC) involves replicating human thought processes in complex computerized models, utilizing self-learning systems with data mining, pattern recognition, and natural language processing. This falls under the broader umbrella of Artificial Intelligence (AI) and signal processing, where machine learning algorithms continuously acquire knowledge to perform tasks without human intervention. CC is a key component of the nine driving technologies of Industry 4.0, which includes CPS, IoT, Cloud Computing, and more. These technologies are reshaping industries, requiring seamless integration and alignment with business vision and strategy for optimal value realization. The Boston Consulting Group outlines these technologies as vital for addressing future challenges and unlocking the full potential of Industry 4.0 (Boston-Consulting-Group, 2020). Figure 6 below depicts the nine technologies driving industry 4.0.

3) *Digital Transformation Challenges*

The transition to digital, specifically the implementation of smart factories, brings about significant benefits. However, it also introduces a multitude of challenges such as connectivity, cybersecurity, talent retention, skill acquisition in digital technologies, standardization, and Business Process Reengineering (BPR). Decision-makers involved in the digital transformation of organizations zational

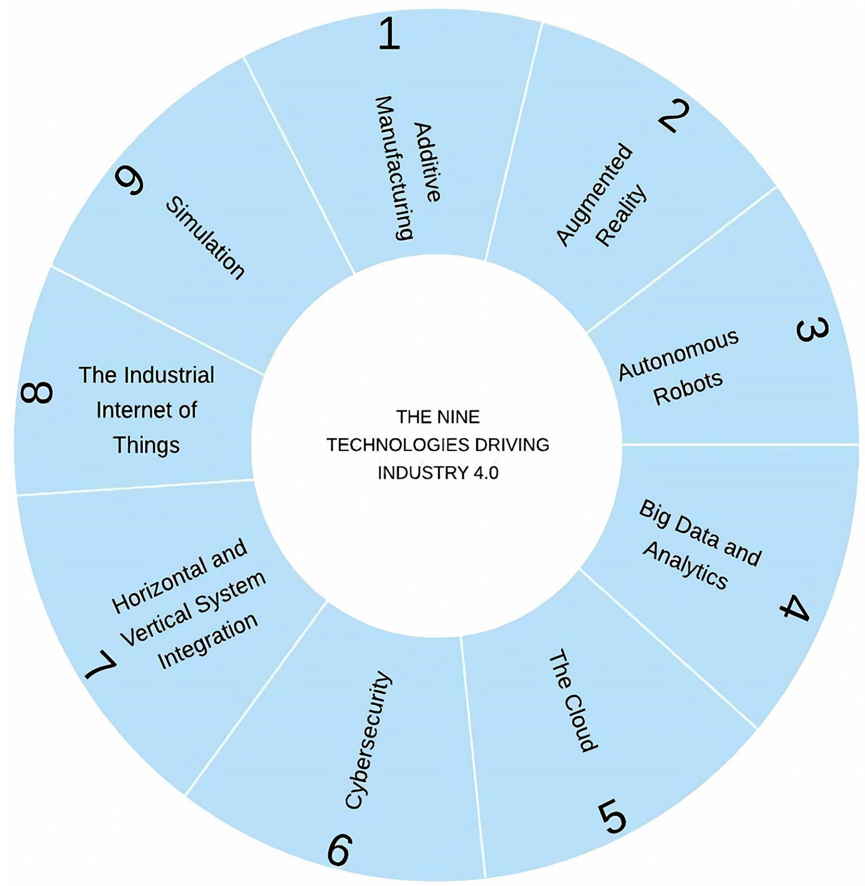

Figure 6. The nine technologies driving industry 4.0 (source: Own representation based on Boston Consulting Group (2020)).

must ensure the successful integration of digital strategy into the overall organi-strategy to achieve digital maturity. Despite the intentions of decision-makers, recent studies in the Quebec manufacturing sector reveal a notable delay in adopting the concept of Industry 4.0 and its associated technologies (Gamache et al., 2020; Québec, 2016; Koch et al., 2014).

The shift in organizational and digital landscapes demands substantial investments in new technologies and cybersecurity to combat cybercrime. Remote management and data exchange, facilitated by IoT and digital transformation, require continuous vigilance to address potential challenges. Organizations must reinvent their business models to adapt to the digital age and identify potential disruptions. However, challenges in organizational, political, economic, and social aspects may impede investment projects related to digital transformation. These challenges are intertwined with the acquisition and storage of big data, digital governance, and the connectivity, automation, and robotization facilitated by IoT and CPS.

To achieve digital maturity, organizations must prioritize information excellence, digital governance, talent acquisition, and retention, along with embracing communication technologies 4.0. Companies that fully comprehend the value of digital maturity, incorporating Industry 4.0 technologies like IoT, CPS, Cloud Computing, and Cognitive Computing, will be well-equipped to address future challenges. A KPMG survey underscores the significance of automation and digital governance across various industries, highlighting emerging trends such as artificial intelligence, machine learning, and the digitization of robotic processes (KPMG, 2018). The report emphasizes addressing strategic, organizational, and operational challenges, as well as talent acquisition and retention, to enhance activities influenced by digital transformation.

7. Conclusion

This research provides pivotal insights into the evolution of manufacturing systems, mapping the transition from Group Technology to Dynamic Cellular Manufacturing Systems. It underscores the critical role of Industry 4.0 technologies in shaping the future of manufacturing, highlighting the necessity for organizations to adapt to digital transformations for sustained competitiveness.

The industry's new era is reshaping organizational futures, presenting both opportunities and challenges that demand swift adaptation for sustained competitiveness. To thrive, organizations must embrace new management methods, optimizing decision-making processes and execution to streamline the value chain. The digital shift, marked by Industry 4.0, introduces challenges in digital technology connectivity, cybersecurity, process standardization, and workforce redefinition. As factories become "*smart*", the adoption of Industry 4.0 technologies emerges as a crucial driver for organizational success across diverse industries.

This study significantly advances theoretical and methodological understanding, offering a foundation for future research and practical applications in manufacturing systems. It paves the way for further exploration into the integration of advanced technologies in manufacturing, emphasizing the importance of adaptability and innovation in an ever-evolving industrial landscape.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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