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TABLE OF CONTENT

DEVELOPMENT OF INNOVATIVE DIGITAL TECHNOLOGIES IN MANUFACTURING

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Abstract. The paper explores the current state and future prospects of innovative digital technologies in manufacturing, emphasizing their pivotal role in achieving sustainable development goals, digitalization, data processing, and artificial intelligence (AI) application. By analyzing trends and emerging directions in modern production, the study aims to align manufacturing practices with sustainable development objectives, integrate high technologies, AI, and enhance overall digitalization across all production stages.

Anticipating the industry's trajectory toward 2030, pivotal trends are identified, including demographic shifts, sustainability imperatives, and technological advancements. As the sector transitions to more sustainable models, digital technologies are poised to play a central role, shaping responsible manufacturing practices and meeting evolving consumer, employee, and regulatory expectations.

The projected advancements in key technologies, such as semiconductor chips, data processing capabilities, and AI systems, present significant opportunities for manufacturers to boost efficiency, competitiveness, and innovation. However, these advancements also necessitate a reevaluation of workforce skills, organizational structures, and human-machine interactions to fully harness the potential of digitalization.

Furthermore, the paper underscores the importance of collaboration between humans and machines, effective data management, ethical AI deployment, and global coordination in manufacturing processes amidst constant change. Highlighting the five technological pillars—electronics, computer systems, software, communications technologies, and cyber infrastructure—the study outlines how advancements in these areas will drive human-machine interaction, automation, and transformative manufacturing practices.

Overall, the adoption of digital technologies promises substantial economic benefits, sustainability gains, and job creation opportunities in manufacturing. The paper concludes by emphasizing the critical role of strategic decision-making, workforce upskilling, innovation prioritization, and ecosystem integration in realizing the full potential of Industry 4.0 technologies for sustainable and competitive manufacturing ecosystems.

Keywords: digital technologies, manufacturing, sustainable development, Industry 4.0, artificial intelligence.

Introduction

Looking back over the past decade, it is safe to assume that industry, especially the machine building sector, has gone through significant changes and is now experiencing one of the most important periods in its 300-year history. Today's production facilities bear little resemblance to their predecessors that existed only a decade ago. They are now highly automated, integrated, constantly monitored, and exchange numerous data and operational instructions using the latest digital tools. The management of manufacturing plants has also evolved, with decision-making at all levels becoming increasingly data-driven. Production lines have become smarter and more interdependent, traditional vertical structures are increasingly being replaced by more horizontal and integrated ones, and former rigid hierarchical organizations are gradually changing to more decentralized, flexible, high-value-added production chain ecosystems.

Considering the expected changes in the industry as we approach 2030 [1], there are several key trends that will reorient almost every manufacturing company in the near future. These trends will affect decision-making processes ranging from investments in factories and plants to product selection, target markets, supply chain organization, and employee engagement strategies. Changes in population growth rates, especially in industrialized countries, are an important factor. By 2030, the number of middle-class people with purchasing power in regions such as the United States, the Eurozone, and Japan is expected to grow at a slow pace of about 0.5%, which is in stark contrast to the significant growth of six percent or more in China and India. Investment in modern skills, innovation and digital infrastructure will be important in determining the location of high-tech industry centers.

Sustainability is increasingly becoming a crucial factor in determining competitive success by 2030. Most industrial leaders already recognize the industry's unique responsibility to become more sustainable. This involves a rapid transition to an organizational form where materials, production processes, energy use, and product life cycles are aligned (fig. 1) with sustainable development goals [2]. The role of digital technologies will be key in achieving this transformation, contributing to the reputation of responsible manufacturing, meeting the growing expectations of customers, employees and investors, and in line with the growing number of global regulations expected in the coming years.

Fig. 1. Sustainable development goals [2]

Without a doubt, the expected progress in key technologies, which will contribute to the rapid digitalization of the industrial sector, opens up huge opportunities for both existing and new manufacturers to improve efficiency and competitiveness. It is predicted [3] that by 2030, a trillion transistors will be installed on semiconductor chips, data volumes will grow by 200-500% over the next few years, and quantum and nanocomputer technologies will significantly increase data processing speeds. Future 6G networks will support terabytes per second data transfer speeds, and increasingly sophisticated artificial intelligence systems will transform huge amounts of data into meaningful analytical insights using various means. The industry must be prepared for the widespread use of these developments.

The future impact of these combined trends on the workforce, and in particular on workers, is likely to be significant. There will be a demand for new skills needed to use, operate, manage and benefit from new technologies. Redefining the relationship between humans and machines will be critical at all levels of the organization to effectively leverage advanced technologies for personal and corporate development. Leadership teams must develop digital competence to master the vast amounts of data available and harness the exponentially growing digital power to create innovative business models and deliver compelling customer experiences.

Recent advances in technology and tools indicate that they will be key to realizing a successful digital transformation over the next decade. Technology education, empowering employees, prioritizing innovation and agility at all levels, and creating a broad, responsive, inclusive, and unified ecosystem will be essential.

One of the key aspects to be considered in order to achieve the Sustainable Development Goals is to understand the effective cooperation between humans and machines, manage the huge flow of data expected in the coming years, decide what should be fully automated and what should not, develop ethical standards for advanced intelligent systems such as artificial intelligence, and align production needs at the national and global level in the face of constant change.

The digitalization of manufacturing, which encompasses key aspects from individual operations to machines, supply chains, and manufacturing ecosystems, is based on five technological pillars: electronics, computer systems, software, communications technologies, and cyber infrastructure. Advances in these technologies over the next decade and beyond will drive the development of human-machine interaction, automation and robotics, and autonomous operations. These advances will improve processes and products, open up new business opportunities, provide pathways to environmental sustainability, and revolutionize manufacturing practices.

Manufacturers will reap the economic benefits of increased productivity, accuracy, efficiency, innovation, and speed, from the factory floor to supply chains and manufacturing ecosystems. In essence, these conditions create the basis for increased competitiveness, sustainable development, and the creation of high-tech jobs. The outlook for the future opportunities of these technologies is extremely positive. According to Allied Market Research, the global digital manufacturing market is expected to reach $1370.3 billion by 2030, up from $276.5 billion in 2020, with a CAGR of 16.5% between 2021 and 2030 [4].

Moreover, the rate of adoption may exceed that of previous generations of technologies. For example, the process of digitalization of production, which involves the transition to digital forms of data and operating systems, has been going on for more than 40 years. In comparison, the time between the invention of the Internet and its implementation on the scale of communication technologies and cyber infrastructure was approximately 20 years. During this same period, data management and computing capabilities have expanded significantly. The technological foundations of digitalization are expected to develop exponentially over the next 10 years.

At the electronics level, the performance curve of semiconductors used in industry is often discussed in the context of Moore's Law. Intel predicts that by 2030, one trillion transistors will be placed on a single chip, which is needed to process the exponentially increasing amounts of data expected from the growing connectivity between physical objects and people in manufacturing ecosystems. Manufacturers expect a significant increase in data volumes, with MLC research showing an expected increase of 200% to 500% within a few years [5].

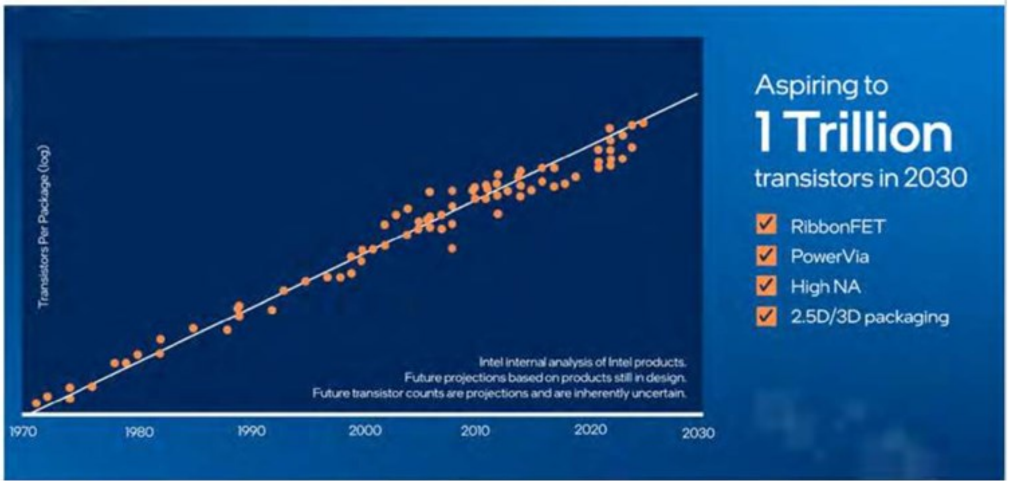

Fig. 2. Intel semiconductor performance curve [5]

As the semiconductor industry grows, so will computer systems. Quantum and nanocomputing are the latest developments that manufacturers should consider, as they have the potential to increase computing power. In particular, traditional computers are expected to become lighter, thinner, and more flexible, and non-standard interfaces such as voice recognition will be actively developed. In the field of communication technologies, 5G networks are expected to spread, providing higher bandwidth and lower latency. The next generation of cellular technology, 6G, which will be available by 2030, is predicted to provide data transfer speeds of one terabyte per second, which will improve image processing, virtual presence, and location technologies.

Improvements in software will lead to the unprecedented development of the next generation of applications that support voice control, augmented and virtual reality. These applications will increasingly use artificial intelligence to support innovation, so it is important to make extensive use of open-source software that can be found online and data sets to accelerate this process.

Strategic decision-making for manufacturers is increasingly linked to the choice of enterprise software architecture and the use of cyber infrastructure. Developed over the past two decades, cyber infrastructure allows for the separation of computer and information resources from their physical sources and methods of use. Cloud computing is an important part of this process, and the integration of on-premises and cloud capabilities with business and technology tools will impact data availability, drive innovation, and shape operating models for business growth.

Artificial intelligence (AI) is becoming a key technology for the future of manufacturing. It is expected that AI will be implemented in various applications and systems in all production processes, ranging from software systems in the factory to robotic systems that help with material assembly and movement, design, modeling, customer interaction, supply chain, and logistics. The potential of AI lies in its ability to recognize, model, predict, and optimize situations, operating conditions, and material properties for both human and machine actions.

AI experts are considering the various roles and factors that can help accelerate its adoption in industry. They have identified three main priorities, each of which is associated with the development of specific applications and datasets: managing assets in production, enabling interactions between assets in factories and supply chains, and promoting logistics sustainability. These priorities are aimed at solving a variety of problems, such as production planning, optimizing energy and material costs, performing preventive and predictive maintenance, and improving production quality.

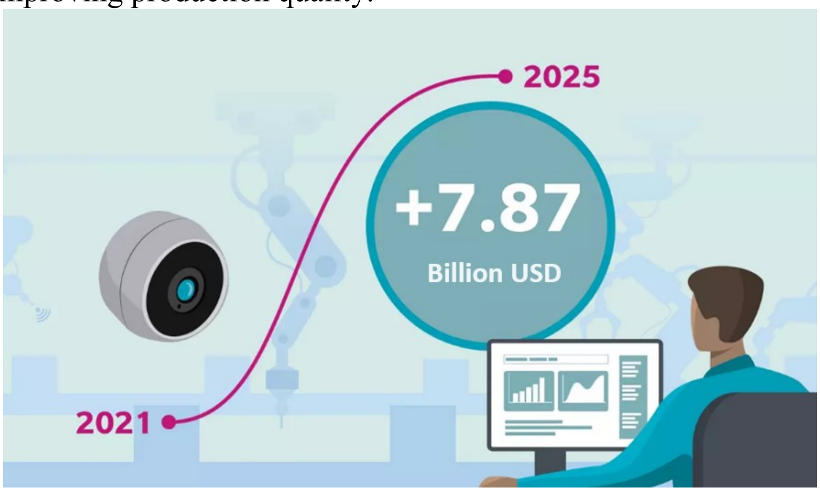

Fig. 3. Projected growth of AI capitalization by 2025 []

Asset management uses industry data and knowledge to create software models to optimize the performance of factory units. However, many manufacturers face a lack of data to draw effective conclusions. Interoperability expands asset management capabilities by sharing assets to improve productivity and efficiency of operations. Supply chain sustainability depends on process transparency and business data analysis, which allows for quick response to any disruptions.

Overall strategies for product safety, environmental sustainability, and decarbonization are implemented through industry supply chains and ecosystem applications. Interoperability is key to these areas, and AI is playing a big role in their implementation, providing significant business relief.

The question of whether the benefits of AI will become widespread is crucial. Widespread adoption of AI requires scaling of processed data and machine learning at the corporate and production levels. Integration of operational and business technologies with privacy and security in mind is critical for successful data exchange in high-tech manufacturing.

An important aspect of progress in manufacturing is a deep understanding of the Industry 4.0 concept, which has been developing over the past decades and creates the preconditions for the transition to the fifth stage of the industrial revolution. Various technologies and methods can be used to implement the measures envisaged by the Industry 4.0 concept in modern industrial production. According to research [8], there are a number of technologies that contribute to the implementation of the concept in the industrial context: Industrial Internet of Things, additive manufacturing, augmented reality, virtual design, horizontal/vertical process integration, cloud technologies, blockchain, cybersecurity, big data, and analytics.

The Industrial Internet of Things (IIoT) is recognized for its reliable connection between the digital and physical worlds. The technology was initially implemented through uniquely identified connected objects using radio frequency identification (RFID). Over time, other technologies have been added to the IIoT, such as sensors, GPS, mobile devices operating via Wi-Fi, Bluetooth, cellular networks, etc. Important elements for the IIoT are barcodes, smartphones, location-based services, service-oriented architecture (SOA), short-range short-wave communications, and integrated industrial computer networks.

Virtual computer-aided design plays an important role in manufacturing, providing integration with physical networks of objects and devices. The production process control system is based on smart devices that integrate equipment, organizational and information systems for data sharing, real-time monitoring and data transfer.

Cloud computing is characterized by the significant amount of data generated by these facility management systems, and it is extremely important and promising. This computing technology offers high performance and efficiency at a low cost. Increasing amounts of data can be easily uploaded to a cloud computing center for storage and processing, which helps to facilitate the maintenance process for operators and reduce production costs. Cloud manufacturing is a dynamic technology that can make a significant contribution to the realization of the Industry 4.0 concept.

Blockchain, in turn, provides the basic structure of a database by connecting data blocks into chains of hashes. It is characterized by a synchronization protocol that allows the blockchain to be constantly updated when new transactions are added. When a new transaction is added to the block, all copies of the blockchain located on other distributed nodes must be updated synchronously. Depending on the specific application, different synchronization protocols can be used to meet security and efficiency requirements. The blockchain is characterized by high information security, thanks to the mathematical principles of asymmetric cryptography, which allows users to enter into transactions with partners even if they do not know each other. It can be integrated with programmable smart contracts, which guarantees reliable and automatic execution of the specified logic thanks to secure encryption.

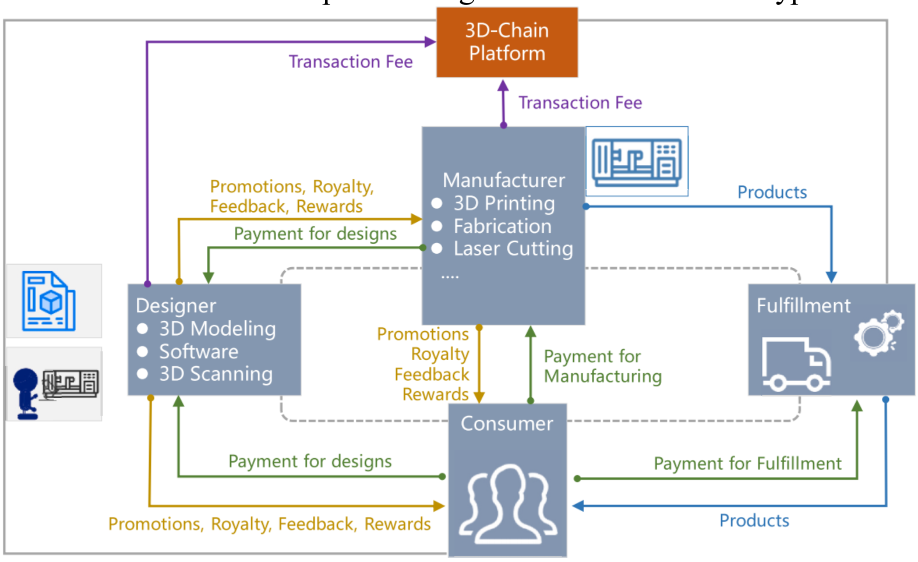

Fig. 4. Workflow of the global blockchain-based manufacturing ecosystem [9]

From a production system perspective, blockchain can be seen as a tool to manage existing production information systems. From a management perspective, blockchain can serve as a tool for collaborative product lifecycle management to create a single database for information exchange.

In many existing industrial production facilities, the information and communication technology infrastructure is not yet ready for a full-fledged digital transformation within Industry 4.0, especially in terms of process integration - horizontal, vertical and cross-cutting. In addition, the Internet of Things (IoT) is a complex heterogeneous network that includes interaction between different types of networks using different communication technologies, which can lead to significant material costs.

Conclusion

The modern manufacturing industry is going through one of the most significant periods of change in its history, driven by the development of digital technologies, growing social responsibility for sustainable development, globalization, and a revision of market geography. In the near future, the industry should be ready for the widespread use of advanced technologies such as semiconductor chips, quantum and nanocomputers, 6G networks, artificial intelligence, augmented and virtual reality, cloud technologies and the corresponding cyber infrastructure. These technologies will allow businesses to increase productivity, accuracy and efficiency in all production processes, as well as create sustainable and integrated ecosystems. At the same time, manufacturers need to develop new skills, establish human-machine interaction, including through education, implement processes for processing and using big data for decision-making, adhere to ethical standards, and take into account global sustainable development goals.

The new digital technologies of Industry 4.0 are opening up opportunities to increase productivity, efficiency, and diversity in current mass production lines. They make it easier to manufacture a variety of products on the same assembly system. Robotization, virtual reality, as well as additive manufacturing and 3D printing, increase productivity and save a significant amount of labor. It is likely that these technologies will transform specialized assembly systems into virtually controlled by artificial intelligence production facilities. Over time, more and more manual operations will be automated. However, the need for specialized engineers to maintain and operate industrial facilities is growing and will continue to grow. At the same time, the requirements for the qualifications of engineers are growing, which, in turn, will lead to an increase in demand for modern engineering education.

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