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Smart Factories and key technologies of Industry 4.0 (review)

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Subject. Industry 4.0 is an approach to manufacturing based on modern information and digital technologies which secure a higher level of production, promote efficient use of materials, reduce repetitive and hazardous jobs, and contribute to sustainable development. Despite extensive research related to Industry 4.0, there is still no single opinion regarding the terminology and technologies which characterise Industry 4.0 and their impact on modern manufacturing. These aspects prove the importance of the research.
Objectives. The article considers the key Industry 4.0 technologies in terms of their impact on modern manufacturing, in particular in relation to Smart Factories. Understanding of the impact of Industry 4.0 technologies on manufacturing will also facilitate their strategic implementation aimed at achieving sustainability.
Method. The authors used the method of analysis of works by Russian and international scientists dedicated to the studied issue, in particular comparative analysis of case studies and practical experience. They also used general scientific methods and methods of logical and comparative analysis.
Results. The article summarises the results of published studies. The authors emphasise the importance of understanding the impact of Industry 4.0 technologies (as a single set) on modern manufacturing, the transition to Smart Factories, and sustainability in the economic, social, and environmental spheres due to increasingly efficient use of resources. The paper also considers key technologies that characterise Industry 4.0 and all together form the foundation for Smart Factories. It emphasises that when applied to manufacturing processes, a full-scale implementation of Industry 4.0 technologies makes manufacturing smart and adaptive. It also defines the cyber-physical system as an important element of Smart Factories.
Results and discussion. The paper emphasises that an integrated implementation of Industry 4.0 technologies is a tool for digital and smart manufacturing that provides the manufacturer with valuable information about the product lifecycle, helps them implement new business models, and connects different manufacturing facilities and events with due account of the time horizon.
Conclusions. It is important to study not only the effectiveness of introduced technologies in each individual case, but also to analyse the impact of Industry 4.0 technologies on manufacturing as a whole. The authors emphasise that the interaction of Industry 4.0 technologies contributes to the creation and development of a new production ecosystem, Smart Factories. They justify the need to identify potential barriers limiting the integration of Industry 4.0 technologies in the considered processes (in particular, the transition to Smart Factories is impossible if enterprises have not passed the stage of digitalisation. Therefore, it is important to create conditions that allow enterprises to reach the modern level of digital manufacturing).

Keywords: sustainable development, manufacturing, strategic implementation, key technologies, cyber-physical system.

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Introduction

The concept of the Fourth Industrial Revolution (Industry 4.0) in reference to the industry appeared with the development and implementation of intelligent, information, and digital technologies which allowed for a higher level of manufacturing and also had an impact on sustainable social and environmental development. Thus, according to Sharma R. et al. [27], the potential of Industry 4.0 (I4.0) is aimed at achieving sustainability in the economic, social, and environmental spheres by increasingly efficient use of resources. In other words, I4.0 is a modern manufacturing system based on the latest information and digital technologies, which contributes to the achievement of sustainability.

Despite a large number of studies related to I4.0, the terminology is still vague: I4.0 remains to be an umbrella term for various technological developments. This may be partly due to the fact the origin of the concept is politically (rather than purely scientifically) motivated since it equally combines political ambitions and technological developments. That is why despite being recognised on the international level, this concept is still criticised since it has no scientific definition, as was noted by Oesterreich & Teuteberg [20].

In 2011, in Germany, German researchers Kagermann et al. [12] introduced the concept of *Industrie 4.0* to determine the future of the German economy "with a high level of automation, operational productivity, and efficiency due to the connection between the physical world and the virtual world". As German scientists understood it, I4.0 was not only characterised as a technological development of the country's industry, it also had a political connotation aimed at supporting "the position of Germany as a leader in industrial engineering[1]."

According to Motyl et al. [19], I4.0 can be defined as production of cyber-physical systems based on heterogeneous integration of data and knowledge. It can be described as an integrated, adapted, and service-oriented manufacturing process which correlates with such I.40 technologies as the Internet of Things, the Industrial Internet of Things, the Internet of Services, Cloud Computing, Big Data Analytics, Additive Manufacturing, Augmented Reality, Robotics, Cybersecurity, etc. Thus, when applied to manufacturing, I4.0 enables system integration, which helps searching and making effective and innovative decisions and makes manufacturing smart and adaptive.

It should be noted that human contribution (which should be improved as a result of developed professional skills of the participants of the process and its stakeholders) is a key element for such integration.

Understanding the impact of I4.0 technologies on modern manufacturing will facilitate the strategic implementation of I4.0 technologies aimed at achieving sustainability, while breakthrough I4.0 technologies can help scientists and practitioners overcome existing technological barriers and achieve not only a high level of manufacturing, but also social and environmental sustainability.

The goal of the study is to consider key I4.0 technologies in terms of their impact on modern manufacturing, including in relation to SF *(Smart Factories)*[2].

To achieve this goal the authors of the paper implemented the following tasks: considered Industry 4.0 technologies, including key technologies contributing to the transition to a Smart Factory; highlighted their impact on manufacturing; identified potential problems (barriers) of integrating such technologies into a SF; provided case stories of the implementation of such technologies (*first part*); studied the

[1] Kagermann H., Wahlster W., Helbig J. Umsetzungsempfehlungen für das Zukunftsprojekt Industrie 4.0: Abschlussbericht des Arbeitskreises Industrie 4.0 // Forschungsunion Wirtschaft – Wissenschaft; Deutsche Akademie der Technikwissenschaften. 2015. URL: https://clck.ru/32kgGq. (In German).

[2] A Smart Factory is a manufacturing system that uses I4.0 technologies, a cyber-physical manufacturing system, and system integration.

contribution of the "smart elements" of the cyber-physical manufacturing system to modern processes of the development/adjustment of manufacturing strategies aimed at achieving set tasks and enabling the transition to a SF where the product design, its production, sale, disposal at the end of its service life, and logistics should reproduce a single scenario of the system integration in accordance with the information stream and with due account of various levels of automation and digitalisation *(second part)*. The final part contains the main conclusions based on the results of the study.

Research Materials and Methods

The methodological apparatus used by the authors included the method of analysis (systematic review) of works by Russian and international scientists dedicated to the studied issue, in particular comparative analysis of case studies and practical experience; general scientific methods; and methods of logical and comparative analysis.

These methods allowed the authors to study the current state of the specified area of knowledge, identify research gaps, analyse and summarise data on the studied issue by synthesising research results, and, in particular to assess the potential of I4.0 technologies for the transition to a SF.

The content analysis of research dedicated to Industry 4.0 showed that different authors have quite similar understanding with regard to which modern technologies relate to I4.0 technologies and the degree of their influence on the processes leading to the transition of manufacturing enterprises to SF and sustainable development. However, that does not exclude the existence of other views on and approaches to this issue.

The conclusions drawn from the research can contribute to future research and the advancement of knowledge about SF and the importance of the strategic implementation of I4.0 technologies in order to achieve sustainable development.

Key Industry 4.0 technologies

*Internet of Things (*IoT) *and Industrial Internet of Things* (IIoT)

The concept of IoT, in which everything is connected, is not new; many efforts have been made to put it into practice. In 1926, Nicola Tesla said in an interview with *Collier's magazine*: "When wireless is perfectly applied the whole earth will be converted into a huge brain"… "and the instruments through which we shall be able to do his will be amazingly simple compared with our present telephone"[3].

Omer Sezer et al. [26] gave a following description of IoT: IoT allows people and things to be connected anytime, anywhere, with anything and anyone, ideally by using any path and/or any network.

IIoT can be described as applying IoT approaches in an industrial context to support the digital transformation of industries. In November 2012, Annunziata and Evans [8] from General Electric published a study which defined IIoT as a combination of achievements in computing, connectivity, and analytics and industrial systems.

Russian researchers, Radov et al. [1], when speaking about IIoT, presented it as a set of methods for processing Big Data (BD) that allow automatic analysis and computing related to manufacturing. In their opinion, IIoT is an important complex information structure that allows smart manufacturing to be supported.

To sum up, it can be argued that IIoT combines manufacturing technologies, BD, intelligent digital technologies, and machine learning to create a new industrial ecosystem.

Internet of Services (IoS)

IoS is understood as the interaction of things that create valuable services with the help of the Internet.

In the context of the product-oriented industry, IoS leads to a shift towards service-

[3] URL: https://clck.ru/32kgL2.

oriented manufacturing, which, in turn, not only improves product quality, but also generates revenue throughout the product lifecycle (forming a "product-service system"). In particular, Andulkar et al. [4] consider IoS as a technology for monitoring product lifecycles.

In this context, IoS is one of the fundamentals of SF.

Cloud Computing (CC)

CC can be considered as an alternative technology for those companies that invest in IT outsourcing. An important advantage of CC is that it allows reducing both indirect and direct IT infrastructure costs.

Yandex Cloud team give the following definition of CC: it is a technology that provides access to computer resources over the Internet; there is no need to buy, store, and maintain physical equipment (these functions are taken over by the cloud provider); the user gets access to the management terminal (where the characteristics of virtual servers are configured and additional services are connected); payment is based on consumption and the volume of resources is practically unlimited (which allows increasing capacity when you need it and disconnecting everything unnecessary).

For direct interaction at the level of the user interface, so-called "*everything as a service*" base layers are used:

1. "*Infrastructure as a Service*" is a place where a cloud service provider provides computing services and/or virtual infrastructure to cloud users so that they could run off-the-shelf software.

2. *"Platform as a Service"* is where cloud users can develop/run their applications which have been developed using programming languages and remote IT platforms.

3. "*Software as a Service"* is where applications are not only hosted, but also run in the cloud infrastructure and cloud users have access to them via their devices (interface). Ooi et al.[21] explain that in this case, we are talking about the use of applications with a lower total cost of ownership, i.e. the use of a technological solution during a certain period of its lifecycle.

However, in the production environment, the so-called concept of "*Cloud Manufacturing"* (CM) is used, which is aimed at improving manufacturing systems using CC technologies. The main characteristic of CM is a shift from a production-oriented to a service-oriented approach. Thus, CM provides services to users at all stages of the product lifecycle; it provides scalable, cost-effective, flexible solutions as a service (for more details, see e.g. Feng & Huang [9]).

Similar to IoS, the functioning of a SF implies the introduction of CM.

Big data (BD). BD *Analytics*

According to Radov et al., databases mainly consist of technologies for collecting, storing, and managing data; technologies for data pre-processing; and technologies for analysis and visualisation [1].

Cemernek et al. [6] understand BD as "large volumes of high velocity, complex and variable data that require advanced techniques and technologies to enable the capture, storage, distribution, management, and analysis of the information."

Indeed, the value and relevance of the data is revealed after their appropriate processing and analysis. Therefore, BD Analytics is an important tool of digital manufacturing which provides the manufacturer with valuable and up-to-date information about the product lifecycle and helps in decision-making, etc.

Doruk et al. [25] emphasise that IoT is part of BD, while CC, in its turn, provide for the IT infrastructure.

Additive Manufacturing (AM)

AM is the technology of "creating 3-dimensional objects, parts, things by adding material together, layer-by-layer". Thus, AM helps to produce new products and introduce new business models. It also allows introducing high-performance applications in modern manufacturing. In particular, AM can be used to create prototypes of products/parts, which saves time spent on designing, developing logistics, and establishing new manufacturing processes. In AM, the process of product manufacturing is controlled by software, which makes it a highly digitised process.

An example of AM is "3D printing", which has become an umbrella term for AM. According to Chang et al [7], the next generation of AM processes is likely to be micro- and nano-3D-printing, bioprinting, and 4D-printing (a combination of intelligent materials capable of changing (adapting) their shape and properties).

AM, an important method for digital manufacturing, is one of the key technologies contributing to the transition to a SF. However, the integration of AM into a SF faces a number of challenges. In addition to the lack of connectivity and traceability, companies face difficulties when it comes to establishing an automated and secure AM workflow based on sustainability principles.

The following are basic requirements essential to integrating AM in a smart factory[4].

1. Connectivity and Data management:

In AM, data is being generated continuously, at every stage of production. To ensure that no piece of equipment or bit of data stays in isolation, IIoT is used, which enables increased connectivity and data-gathering capabilities, through the use of sensors, transmitters, software, and networking. In addition, IIoT offers the ability to remove the silos between operational technology (AM machines) and information technology (software and networks) to ensure a continuous, real-time transfer of data.

2. Automation

The key to integrating AM in a SF is comprehensive automation, which can replace repetitive human labour. Automation achieved through a combination of hardware and software, as well as robotics and sensors ensures more streamlined processes as part of an end-to-end digital production cycle. AM automation covers all levels of the AM workflow (from design to production and product delivery).

3. Traceability:

In manufacturing, traceability means the ability to track every part and product throughout the manufacturing process, from the moment when raw materials enter the factory to the moment when final products are shipped, which guarantees, among other things, improved quality of AM processes (since the enterprise receives key data and can optimise the processes in case of errors/failures). Traceability is currently one of the key concerns facing companies adopting AM for production. Another challenge is the ability to trace reused materials. One of the solutions to such problems is the development of specialised software and using the advantages of BD Analytics.

4. Sustainability:

In a SF, the traditional linear "take-make-dispose" production model is no longer viable. According to K. A. Fontana and B. A. Yerznkyan [2], smart manufacturing means sustainable manufacturing, where companies pursue a circular economy. AM is often seen as a sustainable technology due to its ability to produce more efficient designs which require fewer materials.

5. End-to-end security:

With traditional manufacturing, the theft of one item will not typically translate into a considerable loss of income. However, with AM, the consequences could be far more severe (for example, unauthorised access to data can have serious implications for businesses). Therefore, concerns about security of I4.0 technologies, in particular AM, are well-founded. As a result, the topic of SF cybersecurity is absolutely crucial (see below more about cybersecurity).

Augmented Reality (AR)

AR can be defined as a set of technologies that integrate in real-time the physical world (as we see it) and digital data by means of modern technologies and programs (electronic

[4] We use public data from *Additive Manufacturing Execution System & Workflow Automation Software* (AMFG), which provides software development services and integrates AM technologies into production. URL: https://clck.ru/32kgPE

devices are used to view reality in combination with virtual elements).

The goal of AR is to increase human productivity by providing people with the information they need to solve specified problems. Application of AR in manufacturing, in particular at a SF, allows solving production problems and making managerial decisions. For example, AR can be used to fill gaps that may arise at the stages of a new product development/launch due to their ability to simultaneously reproduce and manifold reuse digital information at each stage of the manufacturing process. Other promising areas of AR in manufacturing are maintenance and sending repair instructions via mobile applications. AR can also be used for virtual training of employees, etc.

Robots

Pedersen et al. [22] explain that in the current manufacturing paradigm there is a shift from mass production to individual production, which makes it adapt to a wider variety of products. To achieve the required level of flexibility, it is necessary to widely introduce into manufacturing intelligent, adaptive, and flexible robots, which will facilitate and accelerate the production of a variety of products and reduce production costs. In addition, autonomous industrial robots can replace people in dangerous and repetitive jobs.

According to Koch et al. [16], there has recently been developed the concept of collaborative robots (cobots). This is a category of robots designed for direct physical interaction with a person at production sites. Cobots (similar to industrial robots) consist of "a manipulator and a reprogrammable control device, which generates control actions that set the required movements of the manipulator executive bodies".

With the development and wider implementation of SFs, human-cobot collaboration is likely to expand and will gradually eliminate the barrier between humans and robots in manufacturing, which will provide for more available and flexible solutions.

Cybersecurity (CS)

CS involves technologies that provide information security. Their main purpose is to detect, respond to, and protect against external and internal cyber attacks, including in an industrial environment (Kannus & Ilvonen [13]). Virtual environments, IoT, data from cloud storage, etc. are most vulnerable.

Cyber attacks can pose a serious threat, including to industrial control systems (CoS)[5]. For example, the interference with physical industrial facilities (as opposed to hacker attacks targeting exclusively information systems) can lead to serious emergencies (in particular in chemical industries), suspension/delays in manufacturing, which, in turn, leads to financial costs, collapse in customer confidence, and other risks.

The vulnerability of industrial CoSs may be due to the fact that they use open architectures which are often connected to external systems;. Yet, most communication protocols for industrial CoSs have been developed without due care for CS. Therefore, it is crucial to implement without fail in all industrial CoSs (including SF) CS with automated incident response and a function of constant updating of security features to keep them up to date.

Modelling

According to Alcácer & Cruz-Machado [3], the successful implementation of digital manufacturing and the organisation and functioning of a SF is impossible without computer simulation, which allows, *among other things*, to conduct experiments to validate the results of product/process design and configuration, including in real time.

[5] According to Knapp & Langill [15], industrial control systems are "a broad class of automation systems used to provide control and monitoring functionality in manufacturing and industrial facilities."

Modern simulation tools have a high potential for optimising real-time decision making (as opposed to process simulation used, for example, to analyse what-if scenarios). In other words, it is an online simulation that links various manufacturing facilities and events generated by the manufacturing system with due account of the time horizon. This option is extremely important for operational processes of the manufacturing system, for example, when planning manufacturing processes and monitoring maintenance processes in real time.

Pushpa & Kalyani [23] believe that an important area of I4.0 technology modelling is the Digital Twin (DT) technology "a virtual or digitized model of a service, product or a process or any IoT". In other words, DT is a software analogue of a physical object (product) which simulates internal processes, specifications, and the behaviour of the real object (product) under the influence of specified external interference, including climatic. The impact input data can be taken from the sensors of a real device; the data from DT sensors can be later compared with the information from the sensors of a real device to identify, for example, anomalies and their causes. Thus, a DT helps to change the parameters of the equipment/product characteristics, to make improvements faster and safer than when experimenting with real objects[6].

Thus, in the industrial context, several DTs can be developed for any product, which makes it possible to quite accurately predict its state under various conditions and at various operational phases. In this way, DTs allow businesses to track past, current, and future performance indicators throughout the lifecycle of a physical asset.

DT has three components: physical objects, virtual models, and data that connect physical and virtual models. The convergence of BD and DT eliminates barriers between the phases of the product life cycle keeping to a minimum the cycles of new product designing and testing. In addition, DTs can significantly expand the capabilities of CC and IIoT.

Therefore, most researchers agree that DTs are an integral element of a SF.

Russia has been the first country in the world to adopt DT standards. The corresponding document, "Computational Modelling" (GOST R 57700.37–2021 "Computational Models and Modelling. Digital Twins of Products. General Provisions"), was approved by Rosstandart, Federal Technical Regulation and Metrology Agency, and put into effect on 01.01.2022. The national DT standard covers engineering products. The authors of the document noted that it can be used in the future to develop standards that establish DT requirements for various industries. For the first time in the world practice, this document provides a unified definition for the "digital twin of the product": it is a system consisting of a "digital model of the product and bilateral data connections with the product (if a product is available) and (or) its component parts". The document also standardised such concepts as "digital (virtual) testing", "digital (virtual) test bed", "digital (virtual) testing ground".

Another document, a series of Preliminary National Standards (PNST) "Smart Manufacturing. Digital Manufacturing Twins"[7], defines the structure of digital manufacturing twins as "a virtual representation of physical elements of the manufacturing process, such as personnel, manufactured products, assets, and description of processes." According to the approved document, Digital Manufacturing Twin is "a detailed modelling of configurations of physical elements and dynamic modelling of changes in the product, processes, and resources that take place during the manufacturing process."

[6] The article uses data from the electronic version of TADVISER. URL: https://www.tadviser.ru/.

[7] Preliminary National Standard of the Russian Federation (PNST) 429-2020 "Smart Manufacturing. Digital Manufacturing Twins"; OKS 25.040.01, valid from 2021-01-01 to 2024-01-01.

Cyber-Physical System (CPS)

According to Tupa et al. [29], CPS, the key SF technology, is defined as a fusion of "cyber" (electrical and electronic systems) with "physical" elements. In other words, in CPS, a cyber component allows a physical component (e.g., mechanical systems) to interact with the physical world by creating, via data digitisation, its virtual copy that includes the "physical component", a cyber representation.

According to Bocciarelli et al. [5], the CPS model can be described as a control unit with one or more microcontrollers, control sensors, and actuators that interacts with the real world and processes the collected data; the communication interface allows the embedded system to communicate with the cloud or other embedded systems (see e.g. Humayed et al. [10]). Therefore, according to Trappey et al. [28], CPSs "are a collection of transformative technologies for managing interconnected physical and computational capabilities".

For example, the "smart elements" of CPS have advanced intelligence and the ability to communicate with each other. They can participate in planning, choose/independently find new strategies, and adjust manufacturing strategies to achieve the set tasks.

In daily life, CPSs have already been changing our lives thanks to the development of robotic surgery, smart buildings, autonomous cars, etc.

Rojas et al. [24] consider CPSs as "building blocks"[8] of a SF, which are interconnected via digital networks and form a cyber-physical manufacturing system (CPMS)[9], which allows a SF to simultaneously function in physical, digital, and cyber spaces and to propose manufacturing scenarios in real time.

[8] The Building-Blocks concept relies on an abstract definition of a building block that is used to represent many technological phenomena, tasks, and equipment to develop intensifying/traditional process alternatives. URL: https://www.sciencedirect.com/topics/computer-science/building-blocks.

[9] A number of authors, for example Khalid et al. [14], Liu & Xu [17], Wang [30], explore the levels of cooperation and communication of CPMSs during manufacturing processes within a SF.

Results: Smart Factory

In the modern world, the possibilities of smart and classical manufacturing will be combined. The evolution of I4.0 technologies has fundamentally changed the way manufacturing plants operate. They are becoming more interconnected, innovative, which paves the way towards a SF. However, it should be noted that there are still many businesses that are not only far from being "smart" (or evolving towards a SF) but are also far from being digital. Therefore, it is important to create not only conditions for a SF, but also to raise existing enterprises to the modern level of digital manufacturing (Digital Factory)[10].

In the Russian Federation, testing SF technologies are planned to be carried out on testing grounds. The first stage of the "road map" in this area involves creating three structures: a testing ground for the generation of "digital", "smart", and "virtual" factories at the Institute of Institute of Advanced Manufacturing Technology of St. Petersburg Polytechnic University; a testing ground at NPO *Saturn*; and experimental and digital certification centres at the Skolkovo Institute of Science and Technology and Lomonosov Moscow State University[11].

As for scientific research, it often focuses on the process of introducing certain I4.0 technologies in certain enterprises (in industries), analyses their (positive) impact on manufacturing activities and making managerial decisions. However, it does not pay due attention to the issue of integrated implementation of I4.0 technologies enabling the transition of enterprises to the modern level of digital manufacturing and further to a SF, which would also meet the goals of sustainable development. Meanwhile, at a SF, product design, its production, marketing, disposal at the end of its service life (or, depending on the type of product, recycling and recovery (as part

[10] Digital Factory is a type of manufacturing based on "digital modelling and design of customised products from the stage of initial research to the creation of a "smart digital twin" of the product, a physical prototype or a small batch" (this issue is not considered in this study).

[11] See details: URL: https://www.kommersant.ru/doc/3814100.

of introducing the principles of the circular economy)), and logistics are interconnected and reproduce a single scenario of system integration in accordance with the information stream and with due account of various levels of automation and digitalisation. According to Jian [11], SF is based on CPMSs which use key I4.0 technologies. Thus this manufacturing system provides end-to-end system integration across the entire value chain and takes into account the entire product lifecycle. Therefore, it seems important to consider not only the feasibility and effectiveness of the introduction of certain digital technologies in each specified case (in an enterprise or industry), but also to analyse the impact of I4.0 technologies (which make manufacturing smart and adaptive) on manufacturing processes as a whole, which, *among other things*, will contribute to the strategic implementation of such technologies as part of a SF establishment.

Discussion

I4.0 technologies allow ensuring a higher level of manufacturing and contribute to social and sustainable development. Researchers have been recently paying increased attention to the study of issues related to I4.0. However, the impact of such technologies on manufacturing processes and the transition to a SF still has not been studied with a comprehensive approach. Meanwhile, understanding the impact of I4.0 technologies on modern manufacturing processes will contribute to the strategic implementation of I4.0 technologies, economic efficiency of enterprises, and environmental and social sustainability.

The method of reviewing scientific literature dedicated to the studied issue, and in particular a comparative analysis of case studies and practical experience, made it possible to summarise the results of published studies, to define I4.0 as the production of CPS (Motyl et al. [19]), and to determine the contribution of the "smart elements" of CPMSs to the modern processes of the development of manufacturing strategies as an important element required for the transition to a SF, where the product design, its production, sale, disposal at the end of its service life, and logistics allow reproducing a single scenario of system integration in accordance with the information stream and with due account of various levels of automation and digitalisation.

The authors considered the key technologies that characterise I4.0 and all together form the foundation for a SF. They analysed their impact on a SF and emphasised that when applied to manufacturing, a full-scale implementation of I4.0 technologies enables system integration, which helps searching and making effective and innovative decisions and makes manufacturing smart and adaptive.

The study considered and characterised the following key I4.0 technologies: *the Internet of Things, the Industrial Internet of Things, the Internet of Services, Cloud Computing (in particular if we are talking about a manufacturing system, Cloud Manufacturing is used), Big Data and Big Data Analytics, Additive Manufacturing, Augmented Reality, Robots (in particular Cobots), Cybersecurity, Modelling (in particular Digital Twins)* (see e.g. Radov et al. [1], Feng & Huang [9], Kannus et al. [13], Koch et al. [16], Ooi et al. [21], Pishpa & Kalyani [23], Sen et al. [25]).

Cyber-physical systems were identified as the key element of SF: its cyber component allows its physical component to interact with the physical world and create its virtual copy (cyber representation) (see e.g. Humayed et al. [10], Monostori et. al. [18], Trappey et al. [28]). Noteworthy is the viewpoint of Rojas et al. [24], who talks about CPMS, the development and implementation of which allows SF to simultaneously function in physical, digital, and cyber spaces (see e.g. Khalid et al. [14], Liu & Xu [17], Wang et al. [30]).

It is important that the technologies were studied not in isolation from each other, but as a set of I4.0 technologies (which complement and expand each other's capabilities). They represent an important tool for digital and smart manufacturing and online modelling, which allow achieving tasks related to modern manufacturing processes and creating new industrial ecosystems (SF). They provide the manufacturer with valuable information about the product lifecycle and help them to make decisions and introduce new business models and highly efficient applications into modern manufacturing processes. They link various manufacturing facilities and events generated by the manufacturing system with due account of the time horizon, which allows predicting the state of the object/product at various operational phases.

The concept of I4.0, which characterises a modern manufacturing system based on modern information and digital technologies, appeared with the development and implementation of intelligent, information, and digital technologies. Despite a growing number of studies related to I4.0 and I4.0 technologies, the concept of I4.0 is still an umbrella term which is criticised since it has no scientific definition and is rather vague. The viewpoint presented in this paper regarding SF, the importance of strategic full-scale implementation of I4.0 technologies, their role in (impact on) the transition to SF, and the key I4.0 technologies is only a possible way of researching this area, which does not exclude the existence of other views on and approaches to this issue.

Conclusions

Industry 4.0 is founded on advanced information and communication technologies, in particular digital technologies, whose introduction ensures a higher level of manufacturing; contributes to the efficient use of materials; eliminates (reduces) repetitive and physically demanding/hazardous jobs at manufacturing by excluding people from such processes; and contributes to socially and environmentally sustainable development.

In this study, the authors did not focus on investigating the process of introducing specified Industry 4.0 technologies into certain enterprises (industries) and analysing their impact on manufacturing activities. Comparative analysis of case studies and practical experience allowed the authors to summarise the results of published studies. The authors concentrated more on the importance of understanding the impact of Industry 4.0 technologies (as a singe set) on modern manufacturing processes, the transition to Smart Factories, and economic, social, and environmental sustainability due to increasingly efficient use of resources.

The study emphasises that at Smart Factories, product design, production, logistics, sales and (hereinafter within the framework of the circular economy) end-of-life disposal/recycling/recovery are intertwined and reproduce a single scenario of system integration in accordance with the information stream and with due account of different levels of automation and digitalisation. Smart Factories, which rely on cyber-physical manufacturing systems and use key Industry 4.0 technologies, are manufacturing systems that provide end-to-end system integration across the entire value chain and take into account the entire product lifecycle, which contributes to the achievement of sustainable development goals.

The paper considered key Industry 4.0 technologies in the context of their impact on modern manufacturing processes, including in relation to Smart Factories. It was shown that the interaction of key Industry 4.0 technologies contributes to the creation and development of a new production ecosystem (Smart Factory). The study revealed a number of potential problems (barriers) inhibiting the integration of such technologies (in particular, Additive Manufacturing) into Smart Factories. It showed the key role of cyber-physical systems (which was defined as a fusion of “cyber” (electrical and electronic systems) with “physical” elements) at Smart Factories, which allows reproducing a single scenario of system integration in accordance with the information stream and with due account of different levels of automation and digitalisation. The paper also emphasises the importance of protecting industrial control systems to minimise risks arising from the consequences of cyber attacks.

It was concluded that the introduction of innovative digital technologies changes the way manufacturing enterprises operate and makes them more interconnected, innovative, and smart. However, one of the limitations of this process is the fact that a significant number of enterprises have not yet passed the stage of digitalisation (they cannot be considered Digital Factories) without which the transition to Smart Factories is not possible. Therefore, it is important to create conditions not only for the transition to Smart Factories, but also to raise existing enterprises to the modern level of digital manufacturing.

The conclusions presented in the paper can contribute to future research and the advancement of knowledge about Smart Factories and the strategic full-scale implementation of Industry 4.0 technologies aimed at achieving sustainable development. The results of the study can be of interest for the academic community, the stakeholders involved in the industrial manufacturing, and entrepreneurs from small and medium-sized businesses who consider development opportunities by working towards becoming a Smart Factory.

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Conflict of interest

The authors declare the absence of obvious and potential conflicts of interest related to the publication of this article.

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«Умная фабрика» и ключевые технологии Индустрии 4.0 (обзор)

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Предмет. Индустрия 4.0 – это подход к производству, основанный на современных информационных и цифровых технологиях, внедрение которых обеспечивает более высокий уровень производства, способствует эффективному использованию материалов, сокращению монотонной, опасной работы; оказывает влияние на устойчивое развитие. Несмотря на большое количество исследований, связанных с Индустрией 4.0, все еще остается открытым вопрос, касающийся не только самой терминологии, но и технологий, которые характеризуют Индустрию 4.0, и их влияния на современные производственные процессы, что подтверждает актуальность темы исследования.
Цель. Рассмотрение ключевых технологий Индустрии 4.0 в разрезе их влияния на современные производственные процессы, в частности в отношении «Умной фабрики». Понимание степени воздействия технологий Индустрии 4.0 на производственные процессы будет способствовать также стратегическому внедрению подобных технологий для достижения устойчивости.
Метод. Использовались метод анализа отечественной и зарубежной литературы по исследуемому вопросу, в частности сравнительный анализ тематических исследований, практических наработок, а также общенаучные методы познания, методы логического и сравнительного анализа.
Результаты. Обобщены результаты опубликованных исследований, на основе чего авторы подчеркивают важность понимания степени воздействия технологий Индустрии 4.0 (в комплексе) на современные производственные процессы и переход к «Умной фабрике», достижение устойчивости в экономической, социальной и экологической сферах путем повышения эффективности использования ресурсов; рассмотрены ключевые технологии, которые характеризуют Индустрию 4.0 и представляют в совокупности фундаментальную основу «Умной фабрики»; подчеркнуто, что в отношении производственного процесса комплексное внедрение технологий Индустрии 4.0 делает производство умным и адаптивным; киберфизическая система определена как важный элемент «Умной фабрики».
Обсуждение результатов. Подчеркнуто, что комплексное внедрение технологий Индустрии 4.0 является инструментом цифрового и умного производства, предоставляющим производителю ценную информацию о жизненном цикле продукта, помогающим во внедрении новых бизнес-моделей, связывающим различные производственные объекты и события с учетом временного горизонта.
Выводы. Представляется важным изучать не только эффективность внедрения технологий в каждом отдельном случае, но и анализировать степень воздействия технологий Индустрии 4.0 на производственные процессы в целом; подчеркнуто, что взаимодействие технологий Индустрии 4.0 способствует созданию и развитию новой производственной экосистемы – «Умной фабрики»; обоснована необходимость выявления потенциальных барьеров, ограничивающих возможности интеграции технологий Индустрии 4.0 в рассматриваемых процессах (в частности, переход к «Умной фабрике» представляется невозможным, если предприятия не прошли этап цифровизации – важно создавать условия для перевода предприятий на современный уровень цифрового производства).

Ключевые слова: устойчивое развитие, производственные процессы, стратегическое внедрение, ключевые технологии, киберфизическая система.

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