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SPECIAL SECTION

Modern approach to sustainable production in the context of Industry 4.0

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Abstract. Reviewing the current state of knowledge on sustainable production, this paper opens the Special Section entitled "Sustainability in production in the context of Industry 4.0". The fourth industrial revolution (Industry 4.0), which embodies a vision for the future system of manufacturing (production), focuses on how to use contemporary methods (i.e. computerization, robotization, automation, new business models, etc.) to integrate all manufacturing industry systems to achieve sustainability. The idea was introduced in 2011 by the German government to promote automation in manufacturing. This paper shows the state of the art in the application of modern methods in sustainable manufacturing in the context of Industry 4.0. The authors review the past and current state of knowledge in this regard and describe the known limitations, directions for further research, and industrial applications of the most promising ideas and technologies.

Key words: Industry 4.0; industrial development; sustainable development; production; supply chain; digital transformation; automation; Internet of Things.

1. INTRODUCTION

Reviewing the current state of knowledge on sustainable production, this paper opens the Special Section entitled "Sustainability in production in the context of Industry 4.0." The authors discuss the state of the art in the application of contemporary methods (i.e. computerization, robotization, automation, new business models, etc.) in sustainable manufacturing (production), in the context of Industry 4.0 [1]. Industry 4.0 has changed the paradigms previously prevailing in the industry, requiring not only information interoperability of networked production units but also access to real-time data for technical control, production control and optimization [2]. Many large manufacturing companies have achieved a significant level of integration of Industry 4.0 technologies into their Total Productive Maintenance (TPM) practices [3]. The authors review the past and current state of knowledge in this regard and present the known limitations, directions for further research, and industrial applications of the most promising ideas and technologies.

Rather than a future challenge, the digital revolution in the industry is a fact we must face and deal with when planning the development of knowledge and practice in all branches of the industry. The European Union as well as other countries, such as the USA, are looking for ways to educate both engineers and ordinary users about the ethics and safety of new technologies. The (r)evolution must be properly defined by researchers and practicing engineers so that the technological progress can be smoothly implemented, on a wide scale, for the benefit of all stakeholders in the process [4].

There is a research gap regarding the definition of the course of the above-mentioned technological and organizational changes, their scope, and the framework for implementation, which – to be filled – requires further research into the drivers and achievements of Industry 4.0.

A number of aspects of Industry 4.0 must be examined, such as the EU's key industry guidelines, roadmaps, and research findings, as well as strategy delineation, whereby key technologies and concepts are taken into account when implementing the Industry 4.0 paradigm in a comprehensive approach [5–7].

When confronted with new technologies, one can see a lack of legislation or lack of competence on the part of those in power, but also a lack of cooperation with the creators of new technologies or the lack of understanding of the processes of their design (deliberate development from scratch) or the search for new solutions (determining which of the existing solutions can be adapted). This is due to the fact that the development of technologies outpaces that of social awareness or related legislation. Thus, the looming social division into the "digitally thinking" and "digitally excluded" must be heeded and the gap closed [8, 9].

The wide implementation of digital technologies and integration of intelligent systems have given rise to the emergence of new approaches and possibilities in management as well as a new approach on the part of customers. On the other hand,

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the above-mentioned changes have been driven by the growing requirements of customers and a change in their value chain [10, 11].

In preparation for this review, we searched six major bibliographic databases containing publications in English appearing between July 2012 and June 2022 (the last ten years). The selected keywords used included Industry 4.0, circular economy, sustainability, manufacturing, business models, strategy, sustainable supply chains, smart cities, sustainable cities, smart factories, and equivalents. Only 39 papers met the criteria for inclusion in the review.

2. GENESIS OF INDUSTRY 4.0

The fourth industrial revolution (Industry 4.0), which embodies a vision for the future manufacturing system, focuses on enabling automation to integrate all manufacturing industry systems to achieve sustainability. The idea was introduced in 2011 by the German government to promote automation in manufacturing [12]. Industry 4.0 is recognized as one of the main drivers in the development of the digital age [13]. Industry 4.0 in practice means that the industry is entering a new, higher level of digitization, offering intelligent, connected, and decentralized production. The concept of Industry 4.0 aims to develop a coherent framework for maintaining and increasing industrial competitiveness, which means transforming industrial production by enriching conventional industry (suppliers, manufacturers, distributors, innovative products, services, and processes) with digital technologies, automation, and robotics to achieve a highly integrated chain with a new, higher value.

In Industry 4.0, the interests of all stakeholders are important, and social gain comes from the compromise between them. Maximization of profit is no longer the only criterion for evaluating production efficiency, and other values are gaining importance, such as the extent to which the production process affects the environment and the health of workers and residents. The philosophy, involving a wider range of specialists (including scientists), politicians and non-governmental organization (NGO) activists than before, brings about technological, social, and economic changes.

In its essence, it is a completely new socio-economic concept which requires the informed participation of all citizens, as it brings about social changes affecting the key issues of today and tomorrow, from the education system and legal framework through science, research and innovation to the industry, technical standardization, safety, the labor market and the rules of societies, including individual producers and consumers, cities/neighborhoods, states or even larger socio-economic communities.

Supply chains remain a vital component of Industry 4.0, especially in view of the experience of the pandemic period. However, industrial information technologies play a key role here, requiring:

- A fast and secure infrastructure often superimposed (at least partially) on previously operated production lines, warehouses and transport networks which cannot be replaced.
- Regular supplies of up-to-date data (often in real or near real time).
- Effective virtual twin systems, inference, and prediction, ensuring anticipatory planning, although not exactly lean manufacturing.
- Skilled engineering staff, able to make the most of the new production supervision systems.

The assessment and evolution of the Industry 4.0 paradigm require systemic ways of sustainability based, for example, on the perspectives of the Triple Bottom Line, Circular Economy and Sustainable Business Model, to map the area of sustainability and explore key research areas [13]. The systematic mapping review included a search of six bibliographic databases containing publications appearing between January 2012 and April 2020. Of the 4291 papers, only 81 (1.89%) have been classified as relevant. Sustainability within Industry 4.0 accomplishes the tasks of the circular economy by implementing the principles of Industry 4.0, implementing sustainable business models at a strategic level, sustainable supply chains, smart and sustainable cities, and smart factories [13].

Naseem and Yang reviewed 55 papers and proposed a framework identifying the impact of Industry 4.0 technologies on the supply chain (Table 1) [12, 14, 15].

Table 1
Key principles of Industry 4.0 [12, 14, 15]

Principles of Industry 4.0		
Digitization and integration of vertical and horizontal value chains	Digitization of products and value offers	Digital business models and access to customers

The technological part of Industry 4.0 is related to the use of the Cyber-Physical-System (CPS) integrated into industrial processes with production operations and Internet of Things (IoT) technologies. The production processes can be represented by intelligent factories, intelligent products, and extensive value networks (vertical integration: people, machines, and resources; horizontal integration: companies across the value chain as in a social network created by the CPS; end-to-end integration) [15, 16].

3. SUSTAINABILITY AS A CORE FEATURE OF DEVELOPMENT

Sustainable production means the integration of processes and systems capable of producing high-quality products and services using sustainable resources (energy, materials), mitigating environmental and social impacts throughout the life cycle, and being safer for employees, customers, and surrounding communities (Fig. 1) [15, 16].

Today, sustainability is one of the strongest drivers of change in the marketplace, representing an important value, a competitive element and part of a business model [17–19].

The UN Sustainable Development Goals (some other initiatives include the Paris Climate Agreement, European Green

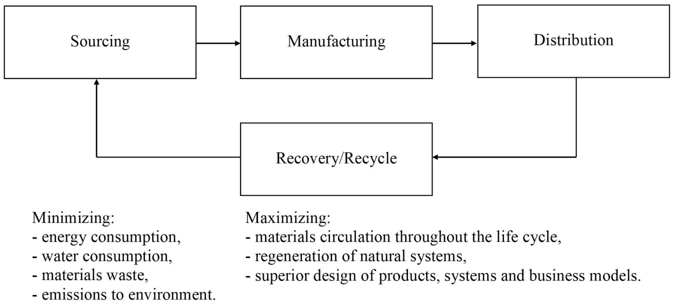

Fig. 1. Circular economy based on sustainable life cycles [15, 16]

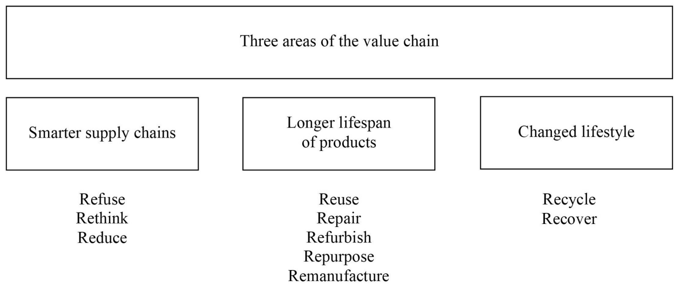

Fig. 2. Influence of circular economy on value chain [14, 17–19]

Deal Circular Economy Action Plan, 2019 African Durban Declaration, circular economy strategies across Latin American countries, China's 5-year Circular Economy Plan, etc.) include various economic, environmental and social attributes, which provide a basis for planning the impact of Industry 4.0 on social and environmental sustainability (Table 2) [14, 15, 20].

However, there is still insufficient analysis and guidance in the academic and practical literature. The benefits of sustainable production include cost reduction through resource efficiency and improving regulatory compliance, strengthening brand reputation, gaining access to new markets, reducing employee turnover through the creation of attractive jobs, and adopting a long-term business approach by creating easier access to finance and capital [15, 21–24].

Organizations need analytical tools supporting reasoned and informed decision–making concerning the implementation of various aspects of Industry 4.0, both in the multi-year strategic perspective of boards and in the day-to-day activities of management (within the current financial year). The use of individual Industry 4.0 technologies to improve sustainability impacts is contingent on a thorough preparatory analysis. Within this framework, each newly introduced technology must be carefully assessed in terms of how strong its impact is on the industry and sustainability (Fig. 2) [14, 17–19].

Sustainable economic growth requires changes to industrial processes, the types and quantities of resources used, and the products manufactured. The world must transform into a more energy-efficient society where resources are used more responsibly, and industrial processes are organized to minimize and reuse waste. Modern technologies affecting all societal activities must reflect the goals of sustainable economic development. The pathways to sustainability lead through changes in the following areas:

- Energy: dependence on fossil fuels is inevitable; nevertheless, we should strive to reduce the use of fossil fuels and apply modern technologies to improve energy efficiency and reduce the pollution caused by fossil fuels, especially in transportation.
- Water: we should seek to streamline its transportation, minimize consumption, and improve the treatment and reuse of water.
- Food: modern technologies enable us to produce more food, improve its storage and distribution, and strengthen disease and drought resistance while reducing the use of such toxic chemicals as pesticides and curbing the negative impact of agriculture on the environment.
- Materials: traditional materials (including plastics) are undergoing significant changes which reduce their environmental impact during production and use, and contemporary materials with extremely specific and strictly controlled properties (more energy-efficient, lighter, and stronger, recyclable) are being designed and created.

Table 2
Key attributes of Industry 4.0 [14, 15, 20]

Technological pillars	Scope of sustainable manufacturing	Industry 4.0 and sustainable manufacturing	Model of the sustainability dynamics
Autonomous robots Simulation Integration of horizontal and vertical system Industrial IoT Cybersecurity Cloud computing Additive manufacturing Augmented reality Big data analytics	Manufacturing technologies (how things are manufactured) Product lifecycle (what is to be produced) Value creation networks (organizational context) Global manufacturing impacts (transition mechanisms towards sustainable manufacturing)	Business model Value creation network Equipment Human factor Organization of smart factories Sustainable manufacturing process Product development	Direct influence on environmental dimension Indirect influence on environmental dimension Direct influence on social dimension Indirect influence on social dimension Direct influence on economical dimension Indirect influence on economical dimension

- Manufacturing and mining: the focus is put on the reduction, reuse and recycling of materials and products in search of industrial ecosystems; moreover, novel approaches and technologies are also being developed and applied to repair past environmental damage [25, 26].
- Public infrastructure is critical to the smooth functioning of society and its ability to achieve sustainable development, especially in areas such as water resources and water supply systems, energy systems, roads and bridges, communications, and transportation facilities.
- Information technology has the potential to change how and where people work and live and thus can shape urban areas in the future and the way businesses are managed, e.g., by improving the efficiency of air, land and water transport systems and monitoring environmental conditions in everyday life.
- Business model: the environment must be given the same consideration as employee safety, costs, and product quality [17].

The manufacturing sector is key to promoting and diffusing technological change, which in turn is a key factor in competitiveness and economic growth.

Properly shaped industrial development supported by modern technology can help achieve many of the goals of sustainable development [18].

Technological innovations play a key role in the industry, especially Industry 4.0 (Fig. 3). They allow for minimizing the impact of industrial activity on the environment and contribute to improving the quality of life and prospects of the societies in which they operate [19].

Sharing economy	Digital technologies	Sustainable & Natural Capital	Waste Minimizing	Longer Life of Products
Shared mobility, production and assembly Equipment rental & leasing Peer-to-peer platforms Product-service economy	Internet of Things Automation & robotics Artificial intelligence Cloud computing Virtual & augmented reality	Alternative energy Sustainable water & agriculture Pollution prevention Plastic alernatives & end-of-life solutions	Biodiversity & land use Raw materials sourcing Toxic emission & waste Other waste (batteries, textiles, plastics, etc.) Water stress	Repair & maintenance Refurbish Reuse Repurpose Recover Recycle

Fig. 3. Sustainable strategies, technologies, and business models within Industry 4.0 [19]

Innovation and sustainability are a complementary pair, as the technological process can be a motivator for generating sustainable behavior. A product or process is now expected to be sustainable simultaneously in environmental, socio-economic, and technological terms [19].

Research on sustainable manufacturing contributes to identifying research programs, mapping ongoing research, consolidating research results, extracting new knowledge from research, identifying gaps and opportunities for research development (including cooperation of various research centers, creation of interdisciplinary consortia), developing the Industry 4.0 paradigm, understanding the links between Industry 4.0 and sustainable production, and creating and correcting the frameworks, principles and technologies of Industry 4.0 [15].

In this way, the ecosystem created by the principles and technologies of Industry 4.0, the scope of sustainable manufacturing, and the opportunities and dimensions of sustainability are generated, maintained, monitored, and upgraded [15].

A review of 35 papers published between 2008 and 2018 by Gonsalvez Machado *et al*. has shown that current research is in line with the objectives of national industrial programs, but research gaps have been identified and development opportunities found to advance the Industry 4.0 agenda [15]. Some progress has been made by Bai *et al*. with a hybrid decision-making method that combines fuzzy sets, cumulative perspective theory and *VlseKriterijumskaOptimizacija I KompromisnoResenje* (VIKOR). It helps to effectively evaluate Industry 4.0 technologies based on their sustainable performance and application, as follows from secondary information sourced from World Economic Forum reports [14].

Previous studies on sustainability requirements for Industry 4.0 cover a wide spectrum of areas, from how Industry 4.0 can support sustainable development and how the technological and industrial revolution can contribute to sustainable production, through intelligent production systems, test stands for sustainable intelligent production and sustainable value creation for smart factories, to integrated networks and processes supporting sustainable design and life cycle assessment, sustainable smart grids and production systems taking into account all stages of the life cycle, and digital management systems for industrial symbiosis [15, 17–19].

There is a gap in the research on sustainability requirements for Industry 4.0 in the areas listed below:

- Business model: integration of physical products and cyber services across their lifecycle; mass customization of a new business model based on new digital and other technologies to enable the transition to a circular and fossil fuel-free economy.
- Production: adaptive, low-emission factories of scalable, high-efficiency manufacturing capacity, able to achieve defect-free manufacturing from closed-loop recyclable materials and providing sustainable, safe, and attractive workplaces to specialists with appropriate knowledge and high qualifications.
- Supply chain: highly integrated energy-efficient and resource-efficient production chains ensuring sufficient production capacity at all stages and a high level of cooperation.
- Product: reused, regenerated, or recycled products ensuring reduced consumption of materials and energy, not containing harmful substances, with a monitored life cycle, where their sustainability boosts their value/attractiveness.
- Policy development: regulation and governance mechanisms as far as transparent and effective licensing and oversight processes encourage/facilitate resource-efficient and environmentally friendly production [15, 27–31].

Effective implementation of a sustainable manufacturing strategy depends on many factors, such as interest-bearing sustainable development policies and procedures, the indicators developed, corporate culture and internal conditions for the implementation and modernization of a sustainable design strategy, and stakeholder involvement in sustainable development and related technologies [15, 32–35].

Gaps in the research and literature indicate where research opportunities still lie. An example often referred to is the sustainability of smart factories in the SME segment – a research area which requires an approach from the social perspective and the perspective of the circular economy. It is well-researched when it comes to environmental management but still poorly studied for its effects on production [15]. Thus, we have fully explored the potential and the factors that influence it, which allows us to achieve good results tailored to fill this research gap but not optimally matched to needs and opportunities. Future research, based on the knowledge and experience gathered so far, should aim to show how to achieve sustainability in the era of Industry 4.0 and optimize utilization of the existing contemporary technologies through integration and application of the same in a new way, tested beforehand [36].

4. INFLUENCE OF CONTEMPORARY TECHNOLOGIES ON THE SUSTAINABILITY OF PRODUCTION

For the purpose of this study, contemporary technologies are defined as disruptive intelligent and information technologies, initiated by the spread of computers in the 1980s and the gradual emergence of applications developed to achieve ever higher levels of production efficiency (Fig. 4) [14]. The end result of their widespread and full implementation is the fourth industrial revolution (Industry 4.0).

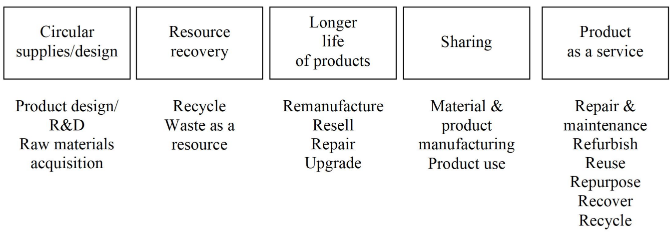

Fig. 4. Five basic business models within sustainable Industry 4.0 [14]

Industry 4.0 is a creative combination of conventional (previously used) and new technologies, including manufacturing processes, materials, production supervision and technical control, communications, cybernetics, cybersecurity, artificial intelligence (optimization, inference, prediction), product life cycle monitoring and sustainable development. Core technologies within Industry 4.0 are autonomous robots, simulation, integration of horizontal and vertical systems, industrial IoT, cybersecurity, cloud computing, additive manufacturing, Augmented Reality, and big data analytics [15].

The impact of new digital technologies on the management of operations takes place both directly, through beneficial effects on efficiency, safety, and ecological sustainability, and indirectly through other factors (e.g., changing organizational culture or strategy on the tactical or operational level) [37].

The relationship between profitability and resources and their management in Industry 4.0 still requires further research. The increasing amount of collected data, which is easy to analyze and to draw long-term conclusions and make predictions based on that analysis, is not without significance. This, in turn, requires monitoring market requirements and technological changes, and the willingness to adopt best practices in the company (Fig. 5) [38, 39].

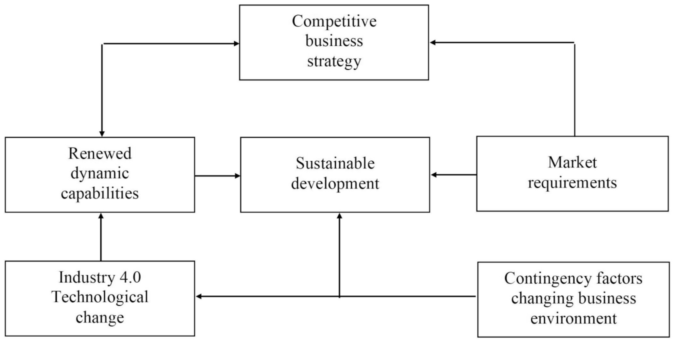

Fig. 5. Research framework: a competitive business strategy can be strengthened by aligning all three dimensions of sustainability while renewing existing capabilities to meet market demands [38, 39]

Many technologies which have the desired characteristics (flexibility, reconfigurability, transformability, low cost, etc.) or which can facilitate the achievement of the same, also fall within the Industry 4.0 paradigm. Some examples are the industrial internet [40], integrated industry [41], the factory of the future [42, 43], Smart Industry and Smart Manufacturing [44–47], and many other emerging technologies.

Emerging technologies within the Industry 4.0 paradigm are aimed at supporting the profound integration of business and engineering processes, ensuring flexible, efficient, and sustainable production, maintaining high product quality, and keeping costs low [15, 47].

The emerging research areas regarding modern technologies in the sustainable development of Industry 4.0 include industrial policy (circular economy, economic factors, development of industrial production, description of added value), Industry 4.0 and sustainable production, industrial Internet of Things and sustainable development, intelligent production (optimization, flexibility, maintenance), sustainable development and life cycle management, Cyber-Physical Systems (CPS), Smart Factory and small and medium-sized enterprises (SMEs), large data sets, among others (logistics 4.0, collaboration, additive manufacturing) [15, 48–52].

Additionally, research into supply chains within the Industry 4.0 paradigm should focus on enterprise management systems (including customer relations) integrating the on-demand product preparation process, intelligent robotic warehouses (for materials, parts, semi-finished and finished products) connected to production lines, intelligent automated transport systems (both intra- and inter-plant), intelligent automated loading systems, shipment tracking systems, and intelligent containers and other intelligent receptacles.

The above-mentioned integration of business information systems requires the combined knowledge, experience and efforts of innovators, system designers and users.

Currently, artificial intelligence in the industry is used primarily for data analysis. The huge amount of data generated by companies is either processed in real time or near real time or used for post-processing. AI facilitates clustering and categorizing data as well as forecasting device, product, or consumer behavior. Marketing and advertising have also undergone a huge transformation, with advertisements learning and optimizing by themselves, and cognitive analysis of graphic, video and audio ads being used to extract sets of color or sound features preferred by customers. The advantages are unquestionable. A bot can answer as many as 1000 phone calls per second, handling more than 70% of inquiries efficiently, which, at an average call length of three minutes, results in 112 thousand resolved issues (70% of 160 thousand answered phone calls) during a standard eight-hour work shift. With shorter calls, the numbers could go to 28 million [53–55]. With time, bots are bound to replace humans in dealing with more difficult, daunting, tedious, and schematic/repeatable tasks, while the human workforce will be able to focus on tasks requiring highly specialized knowledge (supported by second opinion systems), creativity or decision-making based on previously developed options. This digital transformation, automation and robotization will bring about the emergence of many new related professions (positions, jobs), such as digital transformation manager, automation specialist, designer, tester and coordinator of robots, drones, or bots, etc. Thus, robots or bots will relieve the workload of humans, but at the same time, completely new learning, development, and career opportunities will open up for humans.

Many innovations in AI originate from the development of computer games, with the first chess algorithm created in the 1950s. The array of applications of path-finding algorithms is endless, from simple prompts of the next letters or words in an entry or distinguishing hues in a picture or drawing, through predicting stock prices on the stock market, to forecasting the course of a pandemic.

A key problem is that most research into sustainability focuses on conceptual analysis, with particular emphasis on the benefits brought by the Internet of Things [13]. The results of the analysis so far show that mobile technology has the greatest impact on sustainability across all industries, while nanotechnology, mobile technology, simulation, and drones have the greatest impact on sustainability in the automotive, electronics, food, beverage, and textile, clothing and footwear industries, respectively [14, 56–58].

5. DISCUSSION

The digital revolution is happening right now. Automation has become a real business need and procurement processes have accelerated, e.g. bot procurement processes that used to take up to fifteen months now sometimes close in as little as three months. Hence the progressive differentiation into the entire range of scalable solutions available, e.g. from simple robocalls to advanced artificially intelligent voice bots.

The requirements of corporate environments are increasing. Enterprises strive to gain a competitive edge while facing economic (resources, costs, specialists, productivity, product innovation and complexity), social (demanding customers, dynamically changing markets, evolving organizational culture), and environmental (energy efficiency, waste, and climate change) challenges [59–62]. To survive in such a demanding market, they must constantly learn, be flexible and resistant to economic fluctuations, and establish a high management culture as well as reserves of resources and innovations (scientific progress, new software, patents). The reserves of resources also include new, more efficient production technologies (based on automation, robotization, and innovative materials) which support new production processes or build on existing ones [59].

The key factors currently affecting a company's sustainability performance are flexibility, the ability to reduce costs, ways of handling materials, renewing process capabilities, the ability to integrate and reconfigure competencies (both internal and external), and the ability to gather and process information [59]. Competitive advantage is also earned through the smart utilization of engineering experience and specialized production facilities [59].

Growth opportunities are market-driven. The Polish market is characterized by the rapid implementation of innovations and new technologies in the public as well as the private sector, and Polish customers quickly embrace innovations. Poland's location in Central Europe is considered business-friendly and there are many highly qualified programmers. There is sufficient funding for research and many interesting start-ups have been established in recent years. Poland's modern banking sector is open to innovations (e.g., contactless payments are quite widespread in Poland).

With the advantages of the digital revolution, there also come limitations. A real challenge is posed by automatically created social media posts, messages, and emails, which are difficult to distinguish from those written by a person. The Internet can be easily flooded with this fake communication and there is a risk of fake order generation. Hope lies in metadata analysis, which can identify Internet troll farms (who wrote a given post, from where and at what time).

Equally important aspects are legal regulations, artificial intelligence ethics and cyber security. We must bear in mind that it is people who create technology, not the other way around, and we do so for the economic and social benefits that the technology we create brings. We can collect and analyze data in a fraction of a second, computerize, automate, and robotize processes, and improve the work of other people. Therefore, we are also ethically responsible for defining a framework within which technology designers can move, being fully aware that the framework will be breached (e.g., for military purposes) and we should be prepared for this. Rules and laws are only as strong as the ruthless methods behind them for detecting the violation of the same and punishing the violators.

Further development of new technologies is bound to bring them closer to human capabilities and even surpass them where possible. For example, bots handle an increasing percentage of queries ($> 70\%$), they have a memory, understand the context of statements and can recall the right information at the right moment in a conversation. Their accuracy of natural language understanding is constantly being improved, and voice emotion recognition capabilities are growing [53–55].

AI, including that for industrial use, learns from large datasets. The bigger the set, the faster the learning process. In order for AI not to acquire any unconscious bias, the datasets fed must be large and diverse. Corporate datasets which teach systems to plan, control and support production include the mandatory Industry 4.0 set. The requirement applies to all industries; however, it is of particular importance in some (such as, e.g., medical devices and services), considering the restrictions applicable to the processing of personal data.

The conceptual model developed in the course of this study follows the design principles of Industry 4.0, such as decentralization, the interconnection between different systems and subsystems, data transparency (including real-time), control and support, etc. This approach enhances the digitization of the entire value chain and adds sustainability to it, placing the comprehensive digitization of all physical assets and the integration of digital environments in the value chain on a par with environmental, organizational, and legal factors. Never mind that Industry 4.0 encompasses diverse current and future technologies, including cyber-physical systems, Big Data, the Internet of Things, cloud computing, artificial intelligence, and cybersecurity [63]. Intelligent autonomous transport devices or control via brain-computer interfaces and neuroprostheses may be included in this concept in the future.

After all, we must admit that unsustainable industrial development, especially in emerging economies, can create environmental and social risks. Sustainable manufacturing practices prove to boost product quality, market share and the overall profits of an organization, and make it possible to reduce reliance on non-renewable natural resources, and ultimately environmental pollution [64, 65].

This special section is relevant and up to date in relation to the existing literature and what it contributes as it comprehensively captures cutting-edge scientific issues, but at the same time can be almost immediately implemented in business or social activities. Future research directions include:

- AI-based optimization of technological aspects of materials used in 3D-printing processes for selected medical applications and optimization of extrusion-based 3D-printing processes using neural networks for sustainability (including reduction of waste and harmful atmospheric emissions).
- Improvement of device setup accuracy using neural networks.
- AI-based object detection and monitoring for technical control at all stages of design, manufacturing and up to the end of the product life cycle.
- The development of digital twins of technical objects (machines, equipment, software, products, and services), including data acquisition and transformation into knowledge, the use of physical models in simulating tasks and processes, and the use of simulation models to improve physical tasks and processes.
- Integrated eco-design of products and processes, ensuring the appropriate selection of materials and combinations for improved recyclability.

Research on sustainability in Industry 4.0 is increasingly important for the pace and direction not only of the research but also of everyday economic and social practice. Their practical and managerial implications include:

- Changing the approach to the design, manufacture, lifecycle monitoring and disposal of products and services.
- Shaping societal approaches to resource consumption design and recycling and related changes in marketing strategies.
- Paying attention to management decisions based on real data and AI-based predictive models.
- Changes at the societal, strategic, and political level on issues of energy consumption and recognition of its origin (e.g., carbon footprint, renewable energy sources) in the framework of supranational policies (the European Green Deal).

6. CONCLUSIONS

For an increasing number of investors, companies and researchers, sustainable Industry 4.0 represents a broad spectrum of opportunities, especially in terms of new economic models, competitive returns on investment and sustainable ways of doing business, including boosting the company image. The concept of Industry 4.0 presents an opportunity to integrate the ongoing digital transformation into the goals of sustainable development in industrial development [61]. However, markets differ in character and require customized adaptation of the principles of Industry 4.0. Hopefully, this special issue broadens the readers' perspectives on the issue and the proposed research results and technological solutions become an inspiration for further research.

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