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SPECIAL SECTION

The Internet of Things and AI-based optimization within the Industry 4.0 paradigm

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Abstract. By reviewing the current state of the art, this paper opens a Special Section titled "The Internet of Things and AI-driven optimization in the Industry 4.0 paradigm". The topics of this section are part of the broader issues of integration of IoT devices, cloud computing, big data analytics, and artificial intelligence to optimize industrial processes and increase efficiency. It also focuses on how to use modern methods (i.e. computerization, robotization, automation, machine learning, new business models, etc.) to integrate the entire manufacturing industry around current and future economic and social goals. The article presents the state of knowledge on the use of the Internet of Things and optimization based on artificial intelligence within the Industry 4.0 paradigm. The authors review the previous and current state of knowledge in this field and describe known opportunities, limitations, directions for further research, and industrial applications of the most promising ideas and technologies, considering technological, economic, and social opportunities.

Keywords: Industry 4.0; Internet of Things; machine learning; cyber-physical system; industrial Internet of Things.

1. INTRODUCTION

Reviewing the current state of the art on sustainable manufacturing, this article opens a Special Section titled "The Internet of Things and AI-powered optimization within the Industry 4.0 paradigm". Industry 4.0 is a concept launched at the 2011 Hannover Fair in Germany to promote automation in production. The rapid proliferation of the Internet of Things devices is enabling its effective application in many fields: from industry to agriculture, healthcare, and education. Operating at all layers: things, network, and cloud, it facilitates faster data acquisition, computational modeling, inference based on artificial intelligence methods, and control of sensors and effectors assemblies. The ability to integrate legacy network and manufacturing assets into the IoT ensures the digitalization and security of data, resulting in greater reliability and better performance optimization and technical control at every stage of production, which is part of the essence of Industry 4.0, alongside computerization, automation, and robotization [1]. Importantly, currently, the implementation of IoT security standards can better protect stored and transmitted data, apply the most advanced access control mechanisms, and monitor the network for potentially harmful activities, reducing the risk of attack. The use of models provides a basis for the development of data used to make technical decisions, including within so-called virtual twins. This facilitates the reduction of costs, the improvement of product quality, and documenting plans for further development using lessons learned from systems to date. Artificial intelligence (AI) offers techniques for solving problems that cannot be simply described using mathematical methods. This includes not only analyzing the past and present performance of complex systems but also predicting future behavior, including that resulting from natural wear and tear. The article presents the state of knowledge on the use of the Internet of Things and optimization based on artificial intelligence within the Industry 4.0 paradigm. The authors review the previous and current state of knowledge in this field and describe known opportunities, limitations, directions for further research, and industrial applications of the most promising ideas and technologies, considering technological, economic, and social opportunities.

The paper provides an overview of the main research problems centered around the Industry 4.0 paradigm and applications of artificial intelligence. Section 2 discusses the methods behind the selection of representative works and research streams. Section 3 presents the results of the review: the most important research problems and how they are addressed in the literature. Section 4 contains a discussion pointing out the main challenges and risks, but also the directions of development of the discussed methods and future research while Section 5 summarizes the work.

2. METHODS

In this study, we used a systematic literature review. We searched Science Direct and Web of Science databases from January 2017 to March 2023 by searching studies and reviewing papers pub-

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lished at conferences or in journals written in English with the specified keywords (Internet of Things – IoT, Industrial Internet of Things – IIoT, Industry 4.0 – I4.0, machine learning – ML, artificial intelligence – AI and related).

The selection of articles included in the review was carried out as follows: articles meeting the inclusion criteria (above-mentioned keywords, language, and publication date) were included in an initial sample assessment, then reviewed by the authors and selected based on whether they helped to answer the question of the current state of the art in the Internet of Things applications.

3. RESULTS OF THE REVIEW

As part of the current economic and social changes, industrial production, including mass production, is becoming more customer-oriented, providing products and services better tailored to individual needs. This approach increases the pressure on the two-way exchange of information with the customer and the impact on products at all stages of their production [2]. Modern industry has been significantly affected by the effects of the COVID-19 pandemic, both in the area of lack of service, as well as disruption of supply chains and communication restrictions related to the overload of networks and systems with work and remote learning. This results in modifications to the practical implementation of the Internet of Things and Industry 4.0 concepts at all levels: organization, analysis, inference, and prediction from data, networks, sensors, and effectors. Operations performed without or with minimal human participation are slowly becoming the basis of the industry (Fig. 1). This allows you to keep production lines running smoothly, as in the EdgeSDN-I4COVID system, which translates into a significant increase in efficiency [3]. Further improvements in industrial productivity, reliability, and safety are possible primarily using modern control systems that manage and monitor communication between intelligent machines equipped with the appropriate software. Cyber-physical systems (CPS) built in this way form the basis of the fourth industrial revolution (Industry 4.0) [4].

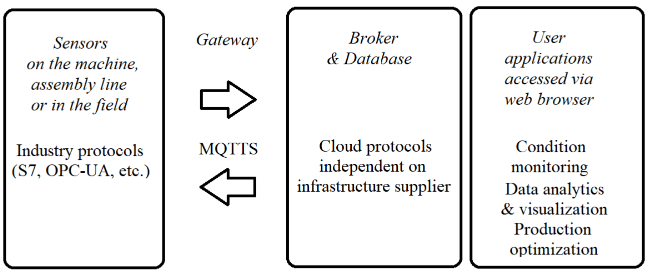

Fig. 1. The schematic infrastructure of IoT processing (MQTTS – Message Queuing Telemetry Transport using TLS – Transport Layer Security) [4]

The Internet of Things (IoT), constituting the technological core of Industry 4.0, ensures the exchange of signals between devices and machines via the Internet, the use of artificial intelligence (AI) techniques for management and control, in line with current trends to optimize resource use, reduce energy consumption, and minimize carbon footprint and pollution. The optimization of energy consumption and savings in the industry uses both artificially intelligent remote management of equipment and detection of the presence of people in individual rooms, which improves decision-making regarding energy consumption [5]. Widespread use of intelligent preventive maintenance of production machinery and equipment is crucial, especially for mission-critical operations. This requires not only reliable and consistent sensor data but also appropriate machine-learning algorithms. Hence the popularity of solutions such as Smart Maintenance Living Lab, i.e., open testing and research platforms [6]. Automation, increased reliability, and control will happen automatically as the integration of many widely deployed intelligent networking and computing technologies increases. Sufficiently high saturation with technologies will allow for the interconnection of various elements, at any place and time, to improve the productivity, efficiency, safety, and intelligence of the production system. The Industrial Internet of Things (IIoT) is distinguished from IoT by its own requirements and properties, both in the area of embedded smart devices, network technologies and quality of service (Figs. 2 and 3), command and control (Figs. 4 and 5) [7].

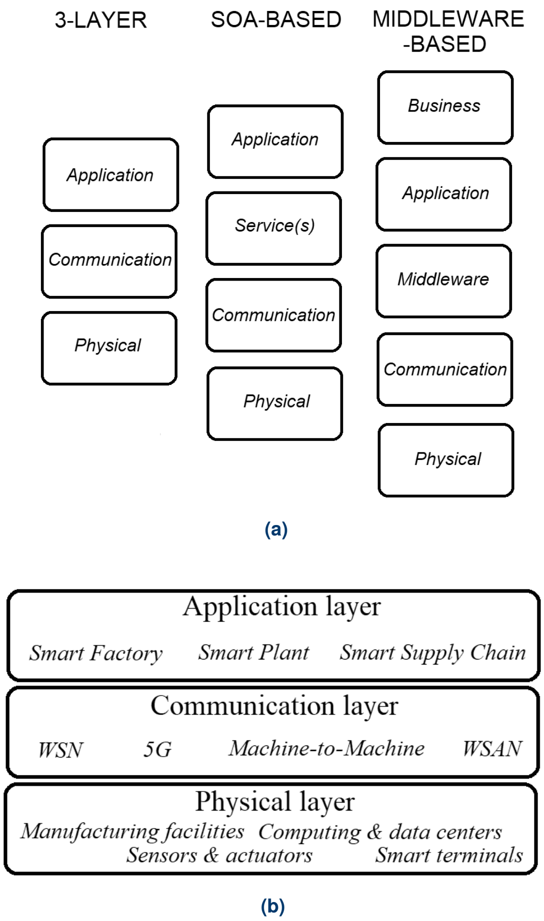

Fig. 2. IIoT system architectures: a) basic kinds, b) details of 3-layer architecture (WSN – Wireless Sensor Network), *5G* – fifth-generation technology standard for broadband cellular networks, WSAN – Wireless Sensor and Actuator Network) [7]

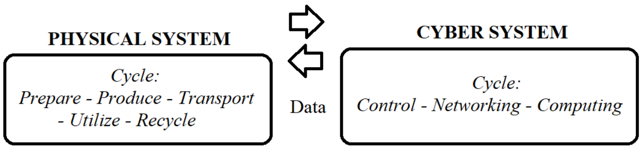

Fig. 3. IIoT from a CPS perspective [7]

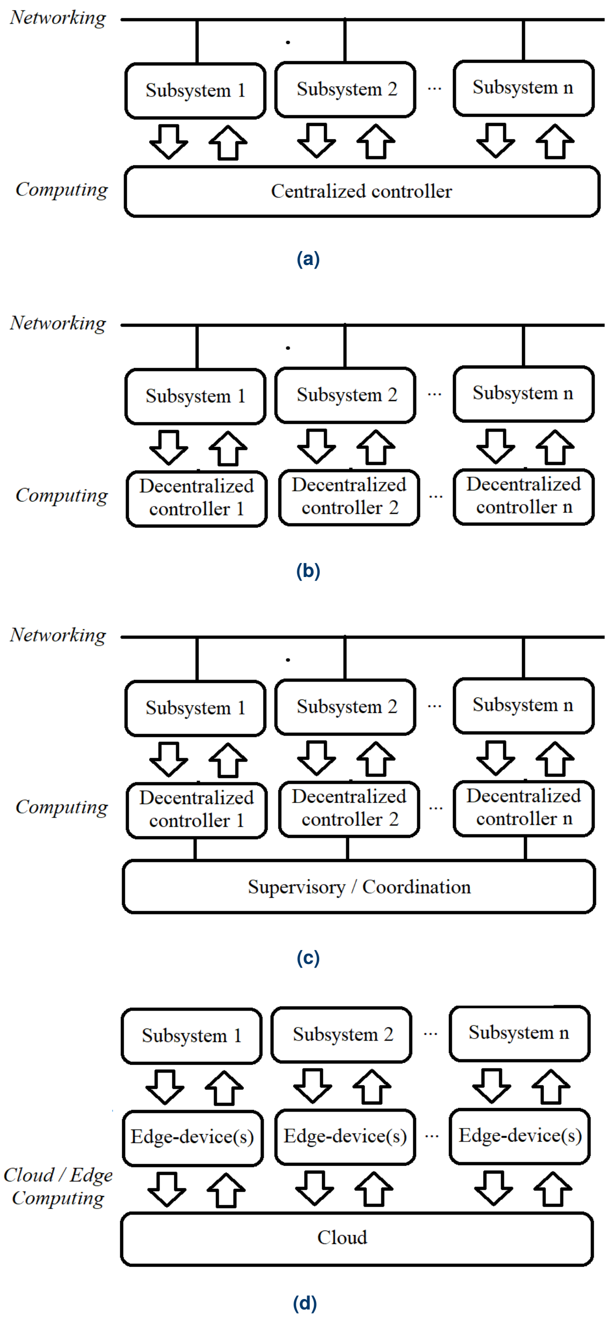

Fig. 4. IoT control architectures: a) centralized control, b) decentralized control, c) hierarchical control, d) cloud control [7]

The security of IoT devices remains a critical issue because existing cyber security solutions cannot be directly implemented due to the limited resources of IoT devices and separate IoT protocols. Hence a need to develop IoT-deduced tools, methods, and data sets, such as IoT-Flock monitoring traffic in IoT networks [8]. The scope of these projects is very wide, as, for example, the implementation of IoT and AI in microalgae farming can contribute to the development of the global microalgae biomass production industry along with the development towards the smart agriculture of the future [9].

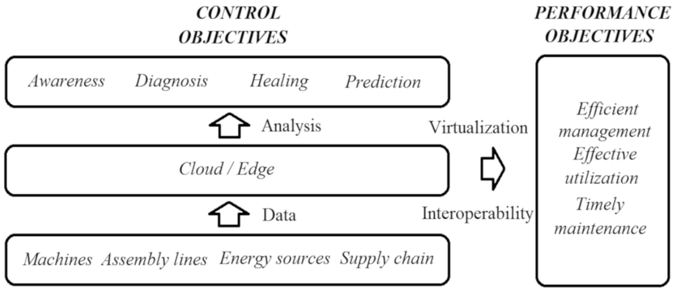

Fig. 5. Objectives of control systems in IIoT [7]

The multiplicity of applications of smart sensors causes smart industrial networks (e.g., power grids) to become increasingly complex, and management – more difficult, due to dynamically changing and sometimes even discontinuous data. This means that conventional models do not work, and it is necessary to use a smart metering infrastructure. It becomes possible not only to manage production but also, based on historical data, to manage demand by eliminating bottlenecks and dispersing suppliers and recipients appropriately [10,11]. The evolution of intelligent industrial sensors consists of the increase of interaction and penetration of various fields, with particular emphasis on wireless sensors, biosensors, and optical sensors, both for general and highly specialized applications [12]. Issues related to maintaining their continuous, reliable operation, calibration (if required), maintenance, and version control remain to be resolved (including interoperability of different models and software versions), including as part of the modernization of both the sensors themselves and other parts of the system, such as cloud computing or machine learning. The use of machine learning (ML) algorithms is aimed at managing groups of sensors and processing the data obtained by them for modeling complex industrial processes. ML and edge computing offer innovative solutions for the industry, especially in the area of data analysis that is difficult to measure in laboratory conditions. The task of the sensor models developed in this way is to continuously monitor production conditions, product quality, and environmental friendliness [13]. Integrated IoT architectures allow for better coping with cheaper and easier implementation of novel solutions and the problem of ML-based cyber attacks [14].

An example of a sector that often lags behind the implementation of Industry 4.0 and IoT technologies is the construction industry (although the design of buildings looks much better, even in African countries) [15]. For comparison, in the railway industry, Industry 4.0 solutions are widely used, especially for maintenance and control tasks for the needs of railway infrastructure [16]. Industry 4.0 is also expected to play a key role in efficient and sustainable forest management (the so-called

Forestry 4.0). This is because climate change is related to maintaining the environmental balance, hence the need to effectively promote sustainable forest management with natural resources utilizing e.g., the Internet of Forest Things (IoFT). At the same time, it is a very demanding environment for the distribution of intelligent devices for collecting data streams when monitoring forests, but also detecting fires [17]. The development of Industry 4.0 allowed for the dynamization of precision livestock farming (PLF) – a modern technological approach to animal husbandry and production in ethical, economic, and logistical terms. Livestock management systems must become efficient if they are to become the basis for suing a growing population. The essential tasks of the system include feeding, analysis of production efficiency, and continuous monitoring of animal parameters [18]. The greatest potential of Industry 4.0 technology has been revealed in the area of stopping the outbreak of the COVID-19 pandemic, both in terms of education and communication, as well as monitoring and responding to threats, including by boosting research and industrial production of medicines and vaccines [19]. In addition to energy, ensuring the continuity of food supply chains and food quality and safety is becoming an important part of Industry 4.0, where IoT, ML, and blockchain ensure the efficient use and optimization of big data sets available in this area [20]. On the other hand, Industry 4.0 offers higher waste management efficiency from a management and productivity point of view. ML is used to automate waste segregation and warn of potential hazards (e.g. noxious waste), radio frequency identification (RFID) and IoT facilitate lifecycle tracking, allowing products to be optimally consumed and recycled promptly, as well as forming elements of larger systems, including cloud-based, filling gaps in traditional waste accounting systems and reducing the cost of monitoring and aggregate analysis [21].

The interruption of many production processes caused by the pandemic or the war in Ukraine may provide an opportunity for Industry 4.0 technologies to test the potential for improving supply chains. This primarily applies to the improvement of time-sensitive solutions during similar emergencies as part of change management as part of rebuilding the supply chain [22].

Brownfield Industry 4.0 stands for smart digitization where various types of previously existing machines and processes must be digitized to be fully incorporated into the Industry 4.0 paradigm (Fig. 6) [23].

In the years 2017–2023, the growth of the number of IoT publications reached an exponential function, with the largest number of publications coming from China and the USA [24]. The most popular concepts in Industry 4.0 are IoT and WSN. They are combined with various control and data analysis systems [25].

Analysis to date shows that Industry 4.0, with its focus on system-scale data exchange and analysis, is becoming a key solution on a global scale in the production of healthcare products and the automation of services in medicine, biology, ecology, and ensuring a safe, comfortable society. It clearly stimulates product and service innovation, the transition to the digital economy, and creativity in the area of multimedia and integrated environments of new, as yet unknown generations [26].

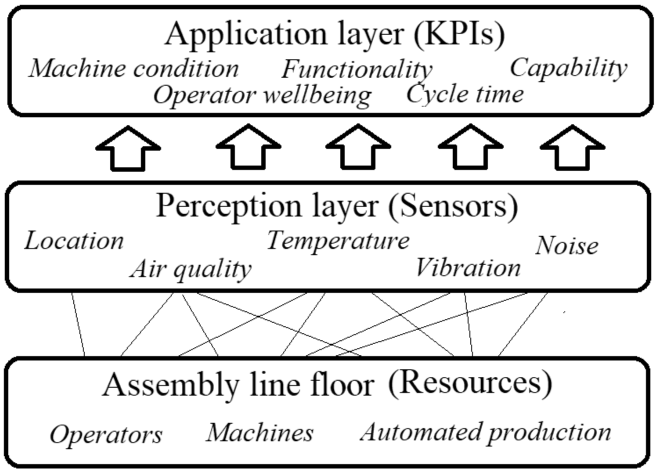

Fig. 6. Determining Key Performance Indicators (KPIs) of the production process from the Industry 4.0 perspective [23]

The direction and quality of the aforementioned developments should be strongly nurtured, as it is the values represented by people, organizations, and societies as a whole that should shape the requirements for technological change, not the other way around (Fig. 7). Smart factories today are already using cyber-physical solutions with higher levels of complexity and accuracy, achieving efficiency, quality, flexibility, transparency, and management of manufacturing processes that legacy technologies will find it difficult to compete with. Customized mass production can lead to unprecedented availability of products and services in selected areas [27]. Increasing the sales of products/services and producers' profits is not the only benefit of Industry 4.0 – it is also about creatively meeting the current problems of the global economy. The increase in the efficiency of production and service provision, improving the quality of customer service, and optimizing the availability of the offer and supply chains became possible thanks to the availability of large sets of raw and analyzed data obtained from sensor networks,

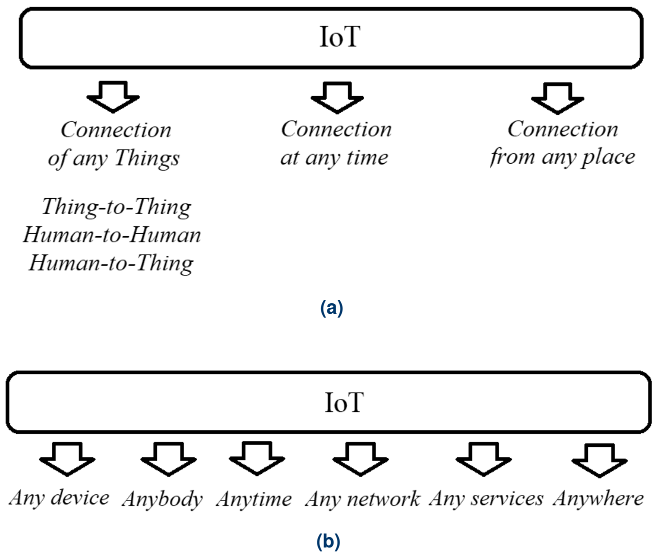

Fig. 7. IoT: a) interconnectivity, b) categories [31]

including optical wireless sensors networks (OWSN). Network latency, throughput, and congestion, as well as packet error rate, are becoming increasingly important, reducing the usefulness of the acquired data in near-real-time optimization [28]. More and more often, the main problem in implementing the discussed group of solutions is the lack of qualified staff (specialist, managerial), and the factors influencing the development of innovative practices in the area of Industry 4.0 are people, customers, culture, strategy, leadership/management, but also the intervention of the state sector [29]. Therefore, not everyone can equally enjoy the benefits of the latest technologies. Rapid and continuous changes resulting from digitization, robotization, and the use of AI change the dynamics of entire industries, and thus the requirements for production, logistics, managerial staff, and sales departments (from innovative business models, such as universal subscription access, Figs. 8 and 9). Redefining future key skills and competences is even present in the food industry, creating roadmaps for future technological, economic, and social changes caused by Industry 4.0, also important for scientists, industry clusters, and professional associations and authorities. Consequently, it will reduce the mismatch between the skills of employees and the requirements of future jobs (Figs. 10 and 11) [30]. This is important because IoT technologies have been recognized as the most commonly used technological tools [31], and therefore their knowledge often determines getting a job (Figs. 12–14).

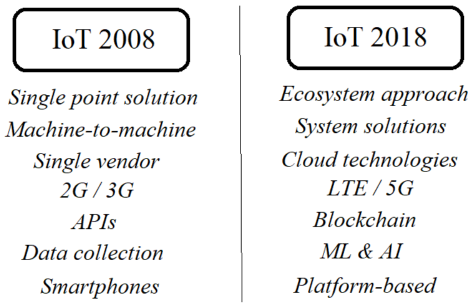

Fig. 8. IoT devices have been smarter in the recent decade [31]

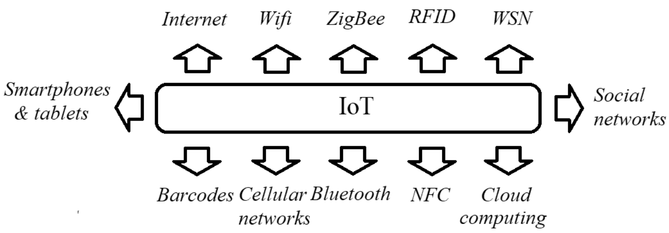

Fig. 9. IoT interconnected with other technologies (NFC – Near Field Communication) [31]

Blockchain technology is also one of the technologies that can be integrated into Industry 4.0 to improve efficiency and security. Blockchain as a decentralized technology cybersecurity, credibility, transparency/audit, and trust building is increasingly used as an element of fintech, medtech, logistics, accounting, or product certification. Despite the publicity, this technology has not yet been fully exploited, new business models based on it are still being created. Blockchain-based smart contracts and mediation systems can ensure automation and real-time application status for Industry 4.0 and Society 5.0 [32]. Safety, preventive maintenance, and process optimization are becoming increasingly important in critical industries (energy, food production, semiconductor industry), and the resulting high reliability and low manufacturing costs have slowly become the standard to which all stakeholders have become accustomed. Detailed knowledge geared to solving specific problems becomes fragmented, sometimes the explanation of the final solution does not provide an exact recipe for the future, and in some cases, the descriptions are too fragmented, relating only to the part of the system being changed [33]. Comprehensive codification and standardization of knowledge and procedures, including inference in the areas of problem-solving, upgrading, and replacement of entire subsystems or their components, is therefore becoming necessary.

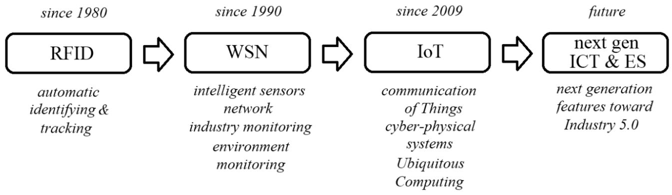

Fig. 10. IoT-related technologies and their importance for emerging future ICT and enterprise systems (ES) [31]

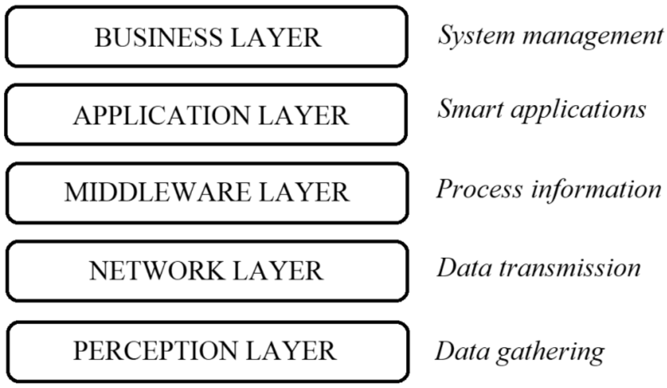

Fig. 11. Five current layers of IoT architecture [31]

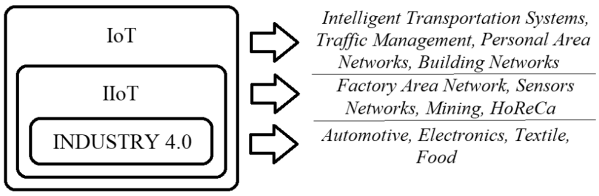

Fig. 12. Proposed potential of the IIoT architecture for the manufacturing industry (HoReCa – Hotels, Restaurants, Catering) [31]

The modernization of the Internet of Things (IoT) standards takes place thanks to the development of ecological 5G communication systems, and thus: higher bandwidth, higher network speed, lower delays, minimum costs, and significantly lower resource consumption. This will increase the speed of data transmission and reliability of connections (including reducing the impact of interference), improving the availability of data from individual devices, and the intelligence of solutions, including mobile ones. The wider introduction of AI to manage 5G networks will avoid the existing compromises in terms of their performance [34].

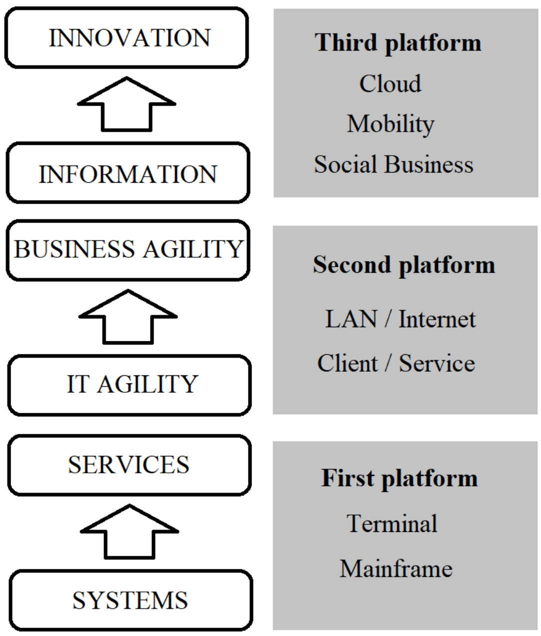

Fig. 13. Platforms across IoT [31]

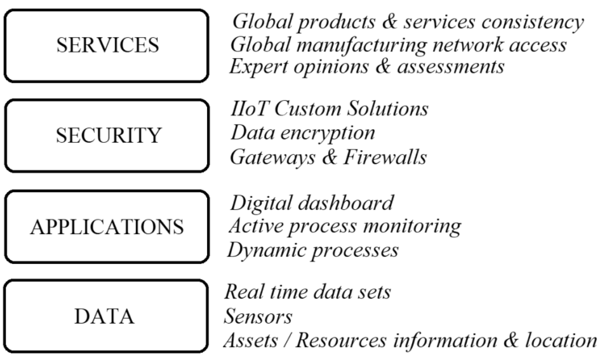

Fig. 14. Value of the IoT through the third platform [31]

Similarly, it will improve logistics and supply chain management with autonomous vehicles, cyber-physical systems, and digital twins, which will improve the identification and tracking of assets, automation, and optimization of the abovementioned areas. This requires the development of cheaper, reliable solutions dedicated to organizations of varied sizes, territories, and organizational complexity, such as accurate indoor positioning based on Ultra-Wideband (UWB) radio technology and RFID-based asset tracking [35].

LPWAN technologies have also the potential to revolutionize the way industrial operations are conducted, by enabling efficient and cost-effective data communication over long distances, which will drive the growth of Industry 4.0 [36]. LPWAN technologies such as LoRaWAN, Sigfox, and NB-IoT are specifically designed to enable low-bandwidth, long-range communication between devices with low power requirements [37]. These technologies allow sensors and devices to be deployed in remote and hard-to-reach areas, enabling monitoring and control of various industrial processes. This makes LPWAN a highly suitable technology for industrial applications such as asset tracking, predictive maintenance, and supply chain management.

Supporting the cost-effective development of low-cost Industry 4.0 applications is difficult due to the limitations of current IoT platforms reflecting the operation of selected large machines and devices, application testing on the production line, and the shortcomings of cost-benefit analysis due to the lack of a sufficiently accurate cost model. A certain proposed solution is Cyber Twins (CT, descriptions, and simulators of machines and devices), which is an extension of the existing Digital Twins concept, as the basis for creating budget Industry 4.0 applications with a cost reduced to 60% of traditional solutions [38].

In addition to the intelligent manufacturing of medical devices, a growing challenge in the area of Industry 4.0 is the intelligent disposal of medical waste, and in some cases, the circular economy to recover single-use products. For these reasons, it is worth considering IoT communication interconnections harmonizing the operation of healthcare centers and waste disposal companies and the joint use of pollution control applications [39, 40].

4. DISCUSSION

Since its very introduction at the Hanover Fair in Germany in 2011, Industry 4.0 has generated strong excitement, including in the area of so-called 'Quantified planets', i.e., the ability to communicate ubiquitously and continuously collect data from sensors embedded in living and inanimate objects, creating novel challenges (Fig. 15) [26].

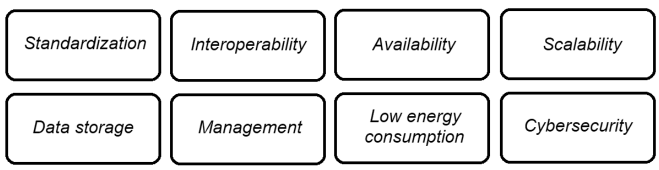

Fig. 15. Technological challenges in the area of AI applications in IoT

4.1. Occupations

Effective machine learning algorithms for analyzing and inferring from sensor data and monitoring and predicting data using industrial digital twins [4]. The reliability of the presented group of systems consists of the correct execution of test environments, obtaining and maintaining data from scalable IoT middleware platforms in the cloud, and dynamic updating of dashboards for monitoring and visualizing the system state based on ML/AI-based analysis and predictions.

4.2. Threats

False data results from inefficient sensors, network communication disruptions, and hacks. They also reflect the detrimental effects of changes in temperature, humidity, numerous industrial sources of interference and noise signals, and loss of data through communication channels [4]. Experts point to the problems of "All Eggs in the One Basket" and so-called network toxicity, i.e., the dependence on the interoperability of components within a highly integrated system, and on the other hand, the need to separate and monitor the use of administrator privileges and deliberately avoid data filter bubbles that can mislead managers of highly automated systems [26].

4.3. Two impressive applications of AI in IoT

AI and IoT in Renewable Energy

Current and future renewable energy systems based on smart solar energy systems, smart DC motors, and energy-efficient electric vehicles rely on applications of IoT solutions supported by artificial intelligence methods, including neural networks, genetic algorithms (GA), fuzzy logic, and a combination of the above. Here, AI and IoT support the planning, design, manufacturing operation, and recycling of low-cost, smart, and efficient solutions for renewable energy systems, and increasingly their performance testing and prediction. This is important because there are countries where renewable energy already accounts for 60% of all energy in the country's energy system, and it is susceptible to, for example, weather changes. ML supported by systems of sensors and IoT effectors is used to predict insolation and temperature not only for grids but also for pricing entire plots, keeping them in working order and predicting repairs and locating upcoming faults, coordinating multiple installations (solar/wind/water/battery resources) and maximizing their efficiency, including in the area of planning consumption and balancing energy storage, detecting anomalies and preventing their effects. The main AI tools used here are based on ML and DL, as far as fuzzy logic [41].

AI in IoT cybersecurity

AI today and in the future will be used to plan and use complex algorithms to protect networks and IoT systems. AI-based attack tools are also emerging. IoT systems can have many vulnerabilities to various attack methods. Typically, today, attacks are combined with one or more ways to protect an IoT system from an attack. As the number and speed of attacks increase, AI-driven, real-time intelligent predictive protection of IoT systems will be required. Such predictive models are not yet commercially common but rather are the subject of research and development and are difficult to implement at every level of the IoT system, also in terms of costs. Just imagine the investment in cybersecurity of a smart factory or smart city. The main AI tools used here are ML, decision trees, k-nearest neighbors (kNN), support vector machines (SVM), and fuzzy logic. The primary areas of AI applications include automation of vulnerability detection, input attacks, data poisoning, and false data injection [42].

4.4. Directions for further research

The essential directions for further development are driven by social and economic priorities, not just by technological possibilities alone. It remains natural to develop in the direction of sustainability and meeting energy and food needs, as well as in the areas of safety, health, science, and work, including their remote varieties.

Priorities set in this way must influence both the strategic objectives, planning, operation, and modernization of IoT/IIoT and AI/ML solutions within Industry 4.0 [43–45]. Greener solutions with a smaller carbon footprint and easier recycling or closed-loop operation will be promoted.

The transition to renewable energy sources and electric vehicles within the European Union alone has the potential to change the picture of the future world, although it will be a multi-year process requiring the modernization of many industrial systems.

Supply chain problems associated with the war in Ukraine, sanctions on some countries, and the post-pandemic crisis are already forcing flexibility on manufacturers and perhaps the introduction of new material solutions.

For the first time, we have a chance for such a broad inclusion of AI in the industrial paradigm – it opens up new possibilities for planning, optimizing, inferring, and predicting production, also with incomplete or uncertain data [46]. In particular, this will affect the optimization of the selection of materials and device settings, including those aiming to reduce the amount of waste and increase the degree of recycling, improve the energy efficiency of devices and entire production lines, increase the accuracy of production, promote wider use of image recognition for error detection and technical control at every stage of production, as well as to ensuring correct operation with incomplete and uncertain data. Virtual twins can improve product planning and testing, but also machine reliability and predictive maintenance, making failures outdated. Digital watermarking could become the next breakthrough in IIoT signals cyber security [47].

5. CONCLUSIONS

When planning the development of Industry 4.0 infrastructure, we must take into account the upcoming planned and expected changes: green deal, energy preferences, ban on the production of combustion cars from 2035, changes in the population of individual countries (entry of generation Z into the labor market, the need to better use Silver Power, etc.), changes in wealth and customer segmentation. Technological changes here will have to keep up with social changes. Domain strategies can force changes at the level of entire industries. Hence, the flexibility of Industry 4.0 will be an advantage here that needs to be used.

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