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A Bibliometric Analysis of the role of Industry 4.0 Sensors in Digital Transformation

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Abstract: This study aims to determine the role of Industry 4.0 sensors in digital transformation. Using a systematic literature review with a bibliometric analysis, we examine a sample of 52 studies from the SCOPUS database to identify research activity on this topic until December 2022. We find that 2022 was the year with the highest number of peer-reviewed documents on the subject, with 18 publications. We also examine current themes and find that sensors can connect multiple systems and devices, thus enabling machine-to-machine communication and facilitating great precision during product designing, development, and production, thus enabling customization and improving quality. However, despite these benefits, the current sensor technologies face multiple challenges that undermine their maximum adoption.

Keywords: industry 4.0; sensors; digital transformation; systematic literature review; bibliometric analysis; VOSviewer

1. Introduction

The fourth industrial revolution, Industry 4.0, encompasses the digital transformation of the manufacturing sector and industrial value chain. It achieves this transformation by integrating ICT, cloud computing, cyber-physical systems, data exchange, retrieval, storage, and security frameworks [1]. The 21st century has seen a rapid transition towards digital transformation, including the digital economy facilitated by developing digital quality infrastructure (DQI). The core goal of Industry 4.0 is to meet individual client demands by improving the functioning of various sectors such as management of orders, research and development, manufacturing operations, distribution and delivery, and product usage and recycling [2]. In addition, it encourages the interconnection of physical goods such as sensors, devices, and corporate assets to one another and the Internet. Therefore, Industry 4.0 enables convergence, cooperation among multiple supply chain stakeholders, and rapid information sharing. These diverse concepts linked to Industry 4.0 paradigm are associated with various constituents contributing to digitalization as identified by Varshney et al. [3] (p.215), including (i) storage and computing capacity, (ii) data transfer speed, (iii) cost efficiency and accessibility of intelligent sensors, (iv) correct use of stored data and information, and (v) advancement of cyber-physical systems. Consequently, the digital transformation resulting from adopting Industry 4.0 technologies leads to opportunities and benefits, including increasing manufacturing productivity, enhancing product quality, reducing operating costs, and supporting product innovation.

However, achieving exceptional capacities in Industry 4.0 technologies requires integrating various intelligent sensors. Varshney et al. [3] explain that sensors facilitate data processing and transfer using electronic mediums or wireless signals. Similarly, Javaid et al. [4] indicate that sensors link multiple systems and devices, allowing the interconnected machines to communicate and track systems and machines in different facilities. Under Industry 4.0, ordinary sensors are turned into intelligent sensors by combining the Internet of things (IoT) and local computational power, thus

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enabling them to calculate the measured data in a complex way locally. Thus, although sensors have played critical roles in production for years, their advancements through Industry 4.0 advanced technologies have expanded their capacities. For instance, intelligent sensors are incredibly compact and highly portable, can be connected to potentially hazardous devices, and are difficult to access. Varshney et al. [3] also indicate that smart sensors integrated into smart manufacturing systems improve process quality measures and parameters. They are calibrated to maintain the highest levels of accuracy using Industry 4.0 technologies such as IoT and other metrological infrastructure. These aspects indicate the essential role of Industry 4.0 sensors in the course of digital transformation. Therefore, this systematic literature review with bibliometric analysis (SLRBA) explores this correlation between Industry 4.0 sensors and digital transformation. A total of 52 documents were analyzed, and their findings were synthesized to create this final report.

2. Materials and Methods

The research employs a systematic literature review with bibliometric analysis (SLRBA) methodology to collect and synthesize data. The procedure was selected based on Donthu et al. [5] description of bibliometric analysis as a rigorous research method used to evaluate developments made in a particular field by demonstrating how certain pieces of evidence connect to structure the study area. In addition, the author argues that the method can be used to unpack the evolutionary nuances of a specific field while providing insights into emerging patterns and trends. In this case, the researcher embraced the SLRBA to explore the development of Industry 4.0, its supported sensor technology, and how these developments shape digital transformation.

The SLRBA involves screening and selecting information sources to ensure the validity and accuracy of the data presented in a process consisting of 3 phases and 6 steps [6,7,8,9] (Table 1).

Table 1. Process of systematic SLRBA.

Fase	Step	Description
Exploration	Step 1	formulating the research problem
	Step 2	searching for appropriate literature
	Step 3	critical appraisal of the selected studies
	Step 4	data synthesis from individual sources
Interpretation	Step 5	reporting findings and recommendations
Communication	Step 6	Presentation of the SLRBA report

This methodological approach focuses on bibliographical research in the online database for indexing scientific articles SCOPUS, one of the essential peer-reviewed databases in the academic world. The isolated use of Scopus is because it is the main source of articles for academic journals/journals, covering about 19,500 titles from more than 5,000 international publishers, including coverage of 16,500 peer-reviewed journals in a variety of scientific, thus providing an objective view of the topics researched with scientific and/or academic relevance. However, we assume that the study has the limitation of considering only the SCOPUS database, excluding other academic databases [6,7,8,9].

The Scopus database was used to identify relevant sources for analysis. The search process began using the keyword "industry 4.0," resulting in 23,300 document results. Adding the keyword "sensors" reduced the document results to 2,870, reducing the articles to 52 by adding the exact keyword "digital transformation". The 52 documents are distributed: 33 conference papers; 14 articles, 4 reviews; and 1 conference review.

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Table 2. Screening Methodology.

Database Scopus	Screening	Publications
Meta-search	keyword: Industry 4.0	23,300
Inclusion Criteria	keyword: Industry 4.0, sensors	2,870
	keyword: Industry 4.0, sensors, digital transformation	52
Screening	Published until December 2022	

Source: own elaboration.

3. Literature analysis: themes and trends

The peer-reviewed documents were analyzed until December 2022. 2022 was the year with the highest number of peer-reviewed documents, with 18 publications. Figure 1 analyzes peer-reviewed publications published through December 2022. The publications were sorted out as follows: Undefined (37); European Regional Development Fund (2); and Horizon 2020 Framework Programme (2); and with 1 the remaining publications.

Until 2022 there was interest in research on Industry 4.0 Sensors Digital Transformation.

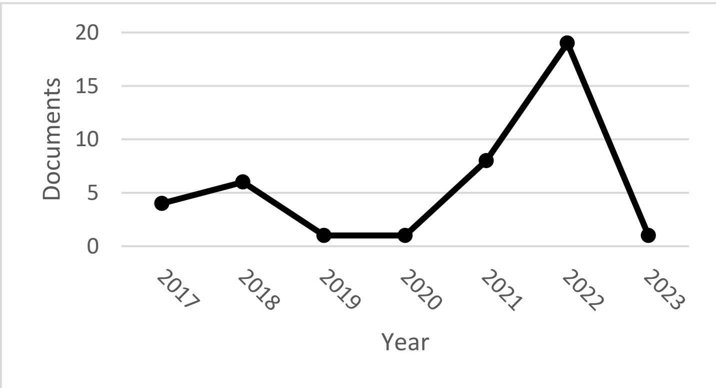

Figure 1. Documents by year. Source: own elaboration.

The thematic areas covered by the 52 scientific and/or academic documents were: Computer Science (29); Engineering (27); Decision Sciences (11); Business, Management and Accounting (8); Physics and Astronomy (4); Agricultural and Biological Sciences (3); Energy (3); Environmental Science (3); Materials Science (3); Chemical Engineering (2); Economics, Econometrics and Finance (2); Social Sciences (2); Earth and Planetary Sciences (1); Mathematics (1); Medicine (1); Psychology (1).

The most cited article was *IoT-enabled smart appliances under industry 4.0: A case study* by Aheleroff et al. (2020), with 127 citations published in Advanced Engineering Informatics with 1,600 (SJR), the best quartile (Q1) and with an H index (90). The objective of this paper is to prove the potential of the Internet of Things (IoT) for reducing cost, improving efficiency and quality, and achieving data-oriented predictive maintenance services.

In Figure 2, we can analyze the evolution of documents' citations until December 2022. The number of citations shows a positive net growth with R2 of 60% for 2022, with 232 citations with a total of 517 citations.

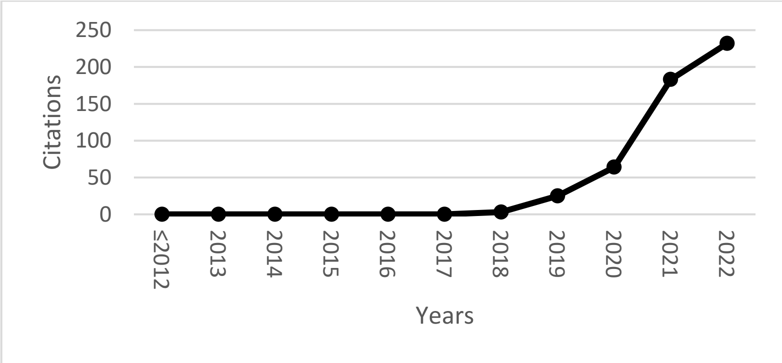

Figure 2. Evolution of citations between ≤2012 and December 2022. Source: own elaboration.

The h-index was used to verify the productivity and impact of published works based on the largest number of articles included that had at least the same number of citations. Of the documents considered for the h-index, 12 were cited at least 12 times.

In Appendix A, Table A1, citations of all scientific and/or academic documents until December 2022 are analyzed; 16 documents were not cited in this period, making a total of 517 citations.

The study of bibliometric results, using the scientific software VOSviewer, aims to identify the main research keywords in studies that are part of the research area of Industry 4.0 sensors in the course of digital transformation. Here, we can see more clearly the most network nodes. The node size represents the occurrence of the keyword, i.e., the number of times the keyword occurs. The link between the nodes indicates the co-occurrence between the keywords, i.e., that occur simultaneously or occur together. Its thickness reveals co-occurrences between the keywords, i.e., the number of times the keywords appear together or co-occur. The larger the node, the greater the occurrence of the keyword, and the thicker the link between the nodes, the greater the occurrence of co-occurrences between the keywords. Each colour represents a thematic cluster, where the nodes and links in that cluster can be used to explain the topic coverage (nodes) of the theme (cluster) and the relationships (links) between the topics (nodes) that manifest under that theme (cluster).

The research was based on the analyzed articles about Industry 4.0 sensors during the digital transformation. The associated keywords are presented in Figures 3 and 4, making clear the network of keywords that appear together/linked in each scientific article, thus allowing us to know the topics studied by the researchers and to identify future research trends.

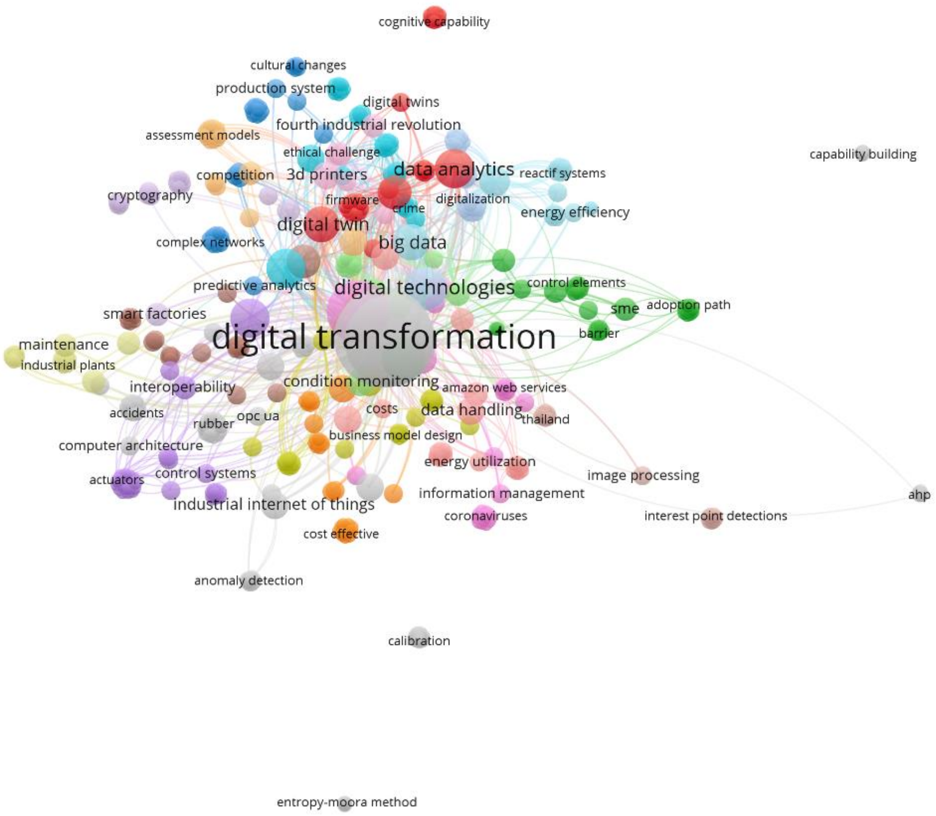

Figure 3. Network of all keywords.

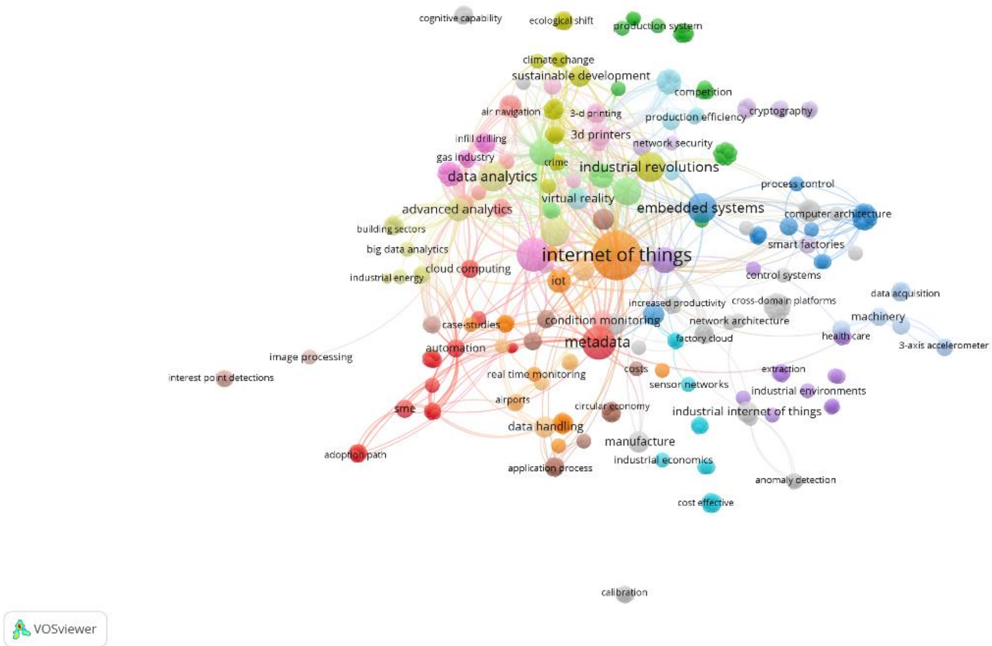

Figure 4. Network of Linked Keywords.

Figure 5 presents a profusion of bibliographic couplings with a cited reference unit of analysis.

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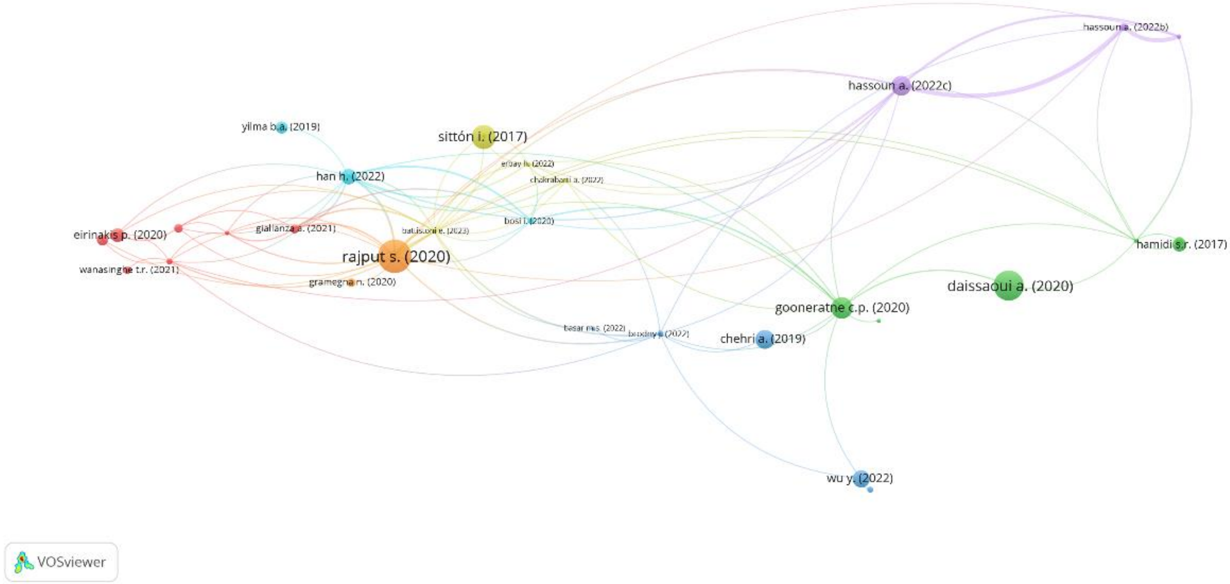

Figure 5. Networks bibliographic coupling.

4. Theoretical perspectives

The manufacturing industry is currently experiencing a rapid digital transformation resulting from the development of Industry 4.0. This fourth industrial revolution is leading the way for advanced technologies such as the Internet of Things (IoT), data analytics, and internet-based services. Unlike Industry 3.0, which focuses on automating single processes and machines, Industry 4.0 supports end-to-end digitalization and integration of all physical assets to create a digital ecosystem connecting all partners within the value chain. Its associated technologies, such as Cloud Computing (CC), the Internet of Things (IoT), Big Data, digital twin, and Additive Manufacturing, are increasingly becoming popular as companies adopt them to increase their competitiveness and improve performance and productivity. The functionality of these interconnected systems requires smart sensors, which help in processing and transferring data through wireless signals or electronic mediums. Therefore, industry 4.0 sensors are critical in facilitating digital transformation under the fourth industrial revolution. This literature review section synthesizes data from selected sources to demonstrate the need for smart sensors under Industry 4.0.

4.1. Defining Digital Transformation

Recent years have seen a rise in new technologies, including big data, social networks, and mobile, which businesses are employing multiple initiatives to explore and exploit. These technologies have transformed critical business operations, affecting products, processes, and organizational structures and prompting companies to establish relevant management practices to manage the changes [10]. Therefore, society is experiencing fast and radical changes resulting from the maturation of digital technologies and their penetration into global markets, causing a major digital transformation. Dallaora et al. [11] define digital transformation as combining information, communication, computing, and connectivity technologies to trigger significant organizational changes that improve operational efficiency, quality of products and services, and overall competitiveness. Schumann et al. [12] explained that digital transformation involves digital modification and description of processes, objects, applications, services, and functions through various systems and subsystems, as shown in Figure 6 below.

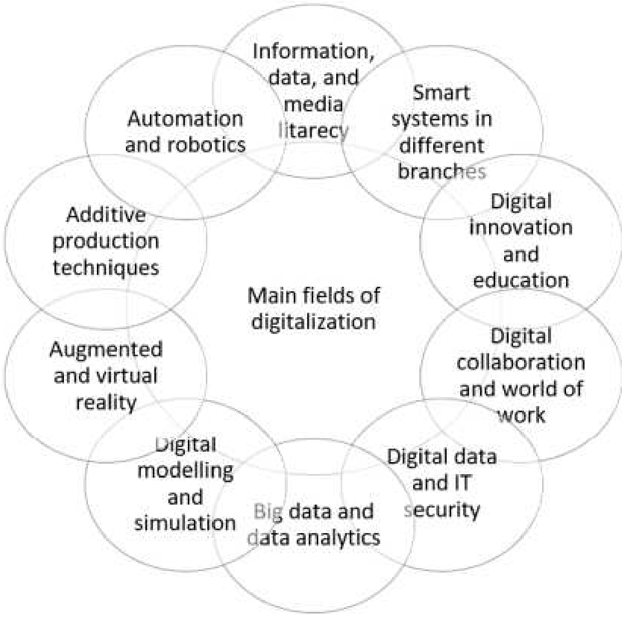

Figure 6. Main fields of digitalization [12].

Industry 4.0 is characterized by multiple innovations, such as smart systems, the Internet of things, and digital ecosystems, which are directly tied to digital transformation. Integrating ICT, cyber-physical systems, cloud computing, data transfer, analysis, storage and retrieval, and cybersecurity frameworks in the industrial and manufacturing sectors under Industry 4.0 is causing digital transformation [13]. These technologies are associated with the four main levers for digital transformation, including automation, digital data, networking, and client access [14]. For instance, smart systems are self-sufficient intelligent technical (sub-) systems characterized by advanced functionality that support the production of upgraded and new industrial and consumer goods and services. In contrast, the Internet of things is a logical extension of the Internet of data and information [15]. Besides, the Internet reflects the world of things rather than ideas since humans physically input data from the real world into digital communication and computation [16]. This makes digital transformation through Industry 4.0 a process through which digital ecosystems connect the real and virtual worlds through advanced technologies.

4.2. Industry 4.0

The origin of Industry 4.0 dates to 2011 in Germany when the federal government introduced "Plattform Industrie 4.0" as a new strategy to promote the development of the country's industrial sector. This German initiative was followed by others across the world, including "Industrial Internet Consortium" in the USA and the "Industrial Value Chain Initiative" in Japan [17]. The industry 4.0 concept is defined as the intelligent networking of industrial machinery and processes using information and communication technologies. It is distinguished by greater automation than the third industrial revolution, the interlinking of the physical and digital worlds facilitated by Industrial IoT [18]. It is also characterized by transitioning from a central industrial control system to one in which smart products describe the production procedures, closed-loop data models and control systems, and product personalization or customization. As a result, Industry 4.0 is seen as the next stage of the industrial revolution [19], with the ability to revolutionize production flow further and alter communication between humans and machines, along with interactions between suppliers, manufacturers, and customers [20]. This transformation is achieved through its main pillars, including the Industrial Internet of Things (IIoT), big data and analytics, additive manufacturing, autonomous robots, Cloud Computing (CC), simulation, horizontal and vertical system integration, Cyber Security, and Cyber-Physical Systems (CPS), and augmented reality.

4.2.1. Internet of Things (IIoT)

The Internet of Things (IoT) refers to an embedded system consisting of interconnected and uniform addressed objects communicating through standard protocols. Wu et al. [21] describe it as the Internet of Everything (IoE) since it incorporates various technologies, including Internet of Manufacturing Services (IoMs), Internet of Service (IoS), Internet of People (IoP), and Integration of Information and Communication Technology (IICT). The diversity of the roles of IoT in today's digital transformation processes is reflected in Chehri and Jeon [22] (p.518) definition of an IoT device as a "resource-constrained embedded system with the capability to perform many well-defined tasks, such as sensing, signal processing, and networking." Three key aspects characterizing IoT are optimization, context, and omnipresence. Optimization refers to expanding systems from a connection to a network of human operators at the human-machine interface. At the same time, context illustrates the ability to interact within an existing environment and respond immediately if something changes using advanced objects [23]. On the other hand, omnipresence provides the advanced object's information, including location, physical, and atmospheric conditions. When IoT technologies are applied in the industrial sector, they form the Industrial IoT (IIoT), which involves creating an intelligent, networked and agile value chain [24]. In addition, IIoT integrates all the resources, processes, systems, and devices across all organizational levels, including human factors, physical objects, smart sensors, intelligent machines, production procedures, and production lines.

4.2.2. Big Data and Analytics

Big data analytics refers to the complex process of analyzing large amounts of data to identify critical information such as hidden patterns, market trends, correlations, and consumer preferences that may assist businesses in making informed decisions. With smart manufacturing under Industry 4.0 and the development of advanced technologies such as artificial intelligence (AI), mobile devices, social media, and the Internet of Things (IoT), the interconnected devices and systems allow companies access to large data volumes, which require advanced tools to analyze and process [25,26]. Therefore, on a large scale, data analytics tools and procedures fill this gap by enabling companies to analyze the high volume, high velocity, and high variety data sets and obtain new insights critical for decision-making and strategizing. According to Bosi et al. [23], the gathering and complete assessment of data from several sources, including manufacturing equipment and systems and corporate and customer management systems, has become common to facilitate real-time decision-making as companies strive to increase performance and productivity in the current competitive global business environment since. This argument is supported by Daissaoui et al. [27] explanation that analysis of previously recorded data is used to determine threats in different production processes earlier in the industry. In addition, it helps anticipate potential future challenges and various solutions to prevent them from happening to stabilize the industry. These aspects illustrate the significance of data-driven strategies and decisions in Industry 4.0 and its associated digital economy.

4.2.3. Additive Manufacturing

Additive manufacturing is a production method that involves connecting successive layers of material to create physical items based on 3D representations. Additive manufacturing technologies are widely employed in Industry 4.0 to manufacture small quantities of customized items characterized by technical benefits such as complex, lightweight designs [28]. Given the continuously changing customer needs and competition in the global market, companies strive to create unique, personalized products that meet consumers' needs [29]. In addition, adopting high-performance, decentralized additive manufacturing technologies have reduced transportation distances and inventory levels [30]. With the use of additive manufacturing technologies such as the fused deposition method (FDM), selective laser melting (SLM), and selective laser sintering (SLS), production has become faster and less expensive.

4.2.4. Autonomous Robots

Robots are increasingly becoming more advanced, independent, adaptable, and cooperative, and they will inevitably communicate with and operate securely alongside people while also learning from them. Under Industry 4.0, an autonomous robot helps businesses perform more accurate independent production and operate in dangerous areas for human employees, thus increasing operational efficiency [31]. In addition, the advancements have proved that autonomous robots can accomplish tasks accurately and intelligently under time constraints while also focusing on safety, adaptability, versatility, and collaboration.

4.2.5. Cloud Computing (Cc)

Cloud computing is considered a significant foundation for Industry 4.0. It refers to delivering computing services, such as servers, intelligence, databases, and storage over the Internet or 'the cloud' [32]. The cloud-based IT platforms have increasingly become the technological backbone for the connectivity and communication of various elements forming the Industry 4.0 Application Centre [33]. As a result, organizations leveraging Industry 4.0 technologies can quickly share data between sites and enterprises, for example, in milliseconds or faster. This innovation has led to the inception of the "digital production" concept, which describes the connection of multiple devices to the same cloud to facilitate fast information sharing from one device to another, and it may be expanded to a collection of machines on a shop floor or the entire plant.

4.2.6. Simulation

Industry 4.0 has expanded the use of simulations in plant operations to harness real-time data that create a virtual model of the physical world, which may include machines, people, and products. This innovative process will reduce machine setup times and enhance quality [34]. In addition, 2D and 3D simulations will be constructed for virtual commissioning and simulation of a manufacturing plant's cycle durations, energy usage, or ergonomic features. Using simulations of manufacturing processes provides multiple benefits, including decreasing downtime and adjustments and reducing production failures during the start-up period [35]. These benefits are achieved through the virtual commissioning process, which enables engineers to spot and eliminate design errors early in the process. In addition, organizational management can leverage simulations to enhance decision-making quality by making the process simple and quick.

4.2.7. Horizontal and Vertical System Integration

The Industry 4.0 framework enhances the fundamental mechanisms utilized in industrial organization, self-optimization, and integration, through advanced technologies. According to Vaidya et al. [32] (p.235), the Industry 4.0 paradigm consists of three main integration dimensions: (a) horizontal integration throughout the whole value creation network, (b) vertical integration, and networked production systems, (c) end-to-end engineering across the product life cycle. The automation of communication and cooperation, particularly along standardized procedures, characterizes the complete digital integration and automation of industrial processes in the vertical and horizontal dimensions.

4.2.8. Cyber Security and Cyber-Physical Systems (CPS)

One major drawback of the Industry 4.0 developments is the increased cybersecurity threats. With Industry 4.0's growing interconnectivity and adoption of standard communications protocols, critical industrial systems and production lines are experiencing more significant cyber security threats, creating the need for advanced protection mechanisms [36,37]. In addition, given the increased demand for tech skills and knowledge, there has been a growing number of hackers, consequently heightening the cyber-attacks and unauthorized access and exploitation of networks, systems, and technologies. As a result, companies recognize the significance of adopting and developing secure, dependable communications, advanced machines, user identification, and access control [38]. CPS systems refer to interacting networks through which natural and artificial systems (physical space) are strongly linked with computing, control, and communication systems (cyberspace) [39]. The interconnectivity in CPS systems makes them a potential risk area for cyber security threats, indicating the need for integrating advanced security networks and mechanisms into an organization's IT infrastructure.

4.2.9. Augmented reality

Augmented-reality systems provide a range of services. For example, an engineer can use mobile devices to relay maintenance instructions or guide another person to choose equipment parts at a warehouse [40,41]. In addition, augmented reality is used in the industry to ensure employees' access to real-time information needed to make informed decisions and improve work practices. Besides, workers may obtain repair instructions on replacing a specific part while inspecting the real system in need of repair.

4.3. Sensors

Various industries use different sensors for varying applications. For instance, some organizations use sensors to connect multiple systems and devices and enable machines to communicate and monitor equipment and systems in each plant. Javaid et al. [4] define a sensor as detecting input stimulus and their corresponding response output. The Input can include force, pressure, flow, heat, light, motion, moisture, or other conditions in the physical environment. The response output is usually in electronic signals, such as voltage, frequency, resistance, capacitance, and current. Integrating IoT and local computational power in Industry 4.0 has helped transform ordinary sensors into intelligent sensors with extended capabilities [42,43]. For instance, these intelligent sensors contain a module that uses complex methods to calculate measured data locally. In addition, smart sensors are incredibly portable and compact. They can be connected to devices considered difficult to access and potentially hazardous, turning them into high-tech intellectuals [46]. As a result, intelligent sensors are changing how manufacturing plants capture and analyze data, especially when paired with IoT, to facilitate smart production and automated manufacturing. These improved functionalities demonstrate the significance of smart sensors in facilitating successful digital transformation under Industry 4.0.

Integrating sensors into an organization's systems provides multiple benefits and opportunities to leverage large amounts of data for effective decision-making. For instance, Gligoric et al. [46] indicate that sensors have a high capacity to process onboard, properly change operations, and evaluate atmosphere conditions. In addition, the scholars explain that their high accuracy levels and ability to analyze data more precisely and rapidly eliminates potential human errors and enhance production and quality with minimal monitoring [42]. As Industry 4.0 continues to evolve, sensors are increasingly becoming more advanced, increasing their capabilities [43]. Industry 4.0, for example, creates a new world that combines modern data processing and cloud-hosted computing with software development, high-level sensor technologies, and smart connectivity [44]. These innovations give a forward-thinking, complete device solution for any manufacturing application that requires intelligent sensors to ensure proper functioning.

4.3.1. Types of sensors

Sensors are categorized based on multiple factors, including what they sense or measure, conversion principles, fields of application, and thermodynamic considerations. For example, pressure sensors measure the pressure of gases and liquids. Research identifies four major types of sensors: nanosensors, microsensors, nuclear sensors, and passive sensors [46]. These are further classified into various subcategories, such as pressure, gas, temperature, light, force, and flow, depending on their specific functions, as summarized in Table 3.

Table 3. Types of Sensors.

Type of Sensor	Description
Data sensors	Provide critical information on features for equipment or system monitoring or repair purposes. In addition, some sensors are used to provide product details or feedback on movement to facilitate precise positioning.
Gas sensors	Gas Sensors are fixed or portable electronic devices that detect the presence and characteristics of various gases and provide output signals to the controller. With numerous safety issues characterizing the manufacturing process, these sensors operate as critical instruments to identify dangerous gases. As a result, they are considered vital in monitoring gas concentration and environmental information.
Temperature sensors	A temperature sensor is an electronic device that monitors the temperature of its surroundings and turns the measured data into electronic data to record, track, or communicate temperature changes.
Force sensors	Force Sensors, sometimes known as load cells, convert applied mechanical forces, such as compressive and tensile forces, into digital signals whose values represent the magnitude of the applied force. These sensors are used in various ways, including consumer goods, medical devices, computer systems, musical instruments, automobiles, and sports equipment.
Flaw sensors	Flaw Sensors/detectors are technologies applied in various industrial processes to detect inconsistencies on surfaces or in different underlying materials. These innovations detect faults in materials using ultrasonic, acoustic, or other methods, making them the most important tool in quality control throughout the production process. In addition, they are also critical in inspecting objects during material analysis and nondestructive testing.
Light sensors	Light sensors, often known as photoelectric devices or photosensors, are invaluable tools used in multiple industries to convert light energy (photons) into electrical signals (electrons). Examples of the most popular types of light-intensity sensors include phototransistors, photoresistors, and photodiodes.
Proximity sensors	A proximity sensor is a device that detects the absence or presence of an object without requiring physical contact. They are built to respond when an item activates the sensor quickly. Because proximity sensors are non-contact devices, they are ideal for dealing with fragile or unstable objects that may be harmed by touch with other types of sensors.

Source: own elaboration.

4.4. Role of Smart Sensors in Industry 4.0 and Digital Transformation

Industry 4.0 is changing and shaping the future of all manufacturing-based sectors. It is causing a transformation where all production activities are based on real-time material knowledge, collected, and analyzed by intelligent sensors and other advanced innovations such as IoT [47]. Smart factories use data to forecast the results of a process stage or function of a system. According to Varshney et al. [3], smart sensors and actuators are critical in the first state of automation, which includes collecting raw data from manufacturing processes and initiating control by analyzing this data. This finding indicates that most operations in the data-driven Industry 4.0 require smart sensors to collect and analyze data that is then used to facilitate other actions and decisions. A similar argument is explained in Javaid et al. [4] research, which indicates that smart sensing technologies are already transforming the manufacturing industry by simplifying integration and analytics. Novák et al. [48] note that wireless sensors are increasingly being integrated into different networks and platforms to enhance communication within data networks and simply data processing. These capabilities enable operators to monitor output easily and improve operational efficiencies.

Additionally, the wide variety of data collected through wireless sensors facilitates better and more agile decisions. Sensors continuously gather and transmit grain data, allowing operators to identify critical insights and patterns in the system's operation while simultaneously allowing decision-makers to identify development opportunities. In addition, sensors allow manufacturers to detect and rectify problems by maintaining, repairing, and upgrading before they disrupt production [42]. As smart sensors advance in Industry 4.0, manufacturers can position them in challenging areas and unsafe equipment and settings. The production equipment may generate massive amounts of data [43]. Smart sensors improve performance efficiency by facilitating real-time data collection, preventative maintenance, remote monitoring, and self-learning.

Sensors play critical roles in the continuous transformation of Industry 4.0 and its integration by businesses in all sectors across the world. They are used to collect data and use computational power to optimize operations based on the type of data collected. As a result, Javaid et al. [4] indicate that the execution and success of Industry 4.0 are based on sensor technology. This is because sensors collect system and machine status data processed and used in process-level information systems and workflows. In this case, sensor technologies are integrated into multiple points throughout the systems to facilitate effective data collection [49]. The ongoing digital transformation driven by Industry 4.0 technologies depends on the extensive use of data, indicating the critical role of smart sensors. Below are some sensor applications in industry 4.0 that are driving the ongoing digitalization:

4.4.1. Linking Multiple Devices and Systems

Manufacturers utilize sensors to increase production efficiency and boost operations since they allow them to reinvent their plants. Intelligent sensors generate data by connecting multiple machines and systems, allowing various devices to communicate [43]. As a result, these sense capabilities enable manufacturers to reduce operational costs by minimizing excess scheduled servicing, replacement expenses, and market disruption capacity. For instance, smart sensors collect and analyze data that allows automated maintenance and identification of risks before they cause any disruptions [45]. In addition, the data obtained using sensors might reveal patterns, indicating that equipment needs to be serviced and provide operators with warnings, preventing them from becoming failure sites [42]. Consequently, these benefits increase operational efficiencies and save the facility from potential expenses and losses that would have resulted from equipment failure or delayed manufacturing practices [50]. Most companies require their suppliers to submit reports demonstrating compliance with routine maintenance practices.

4.4.2. Sensors Enhance Production Performance

Sensors help manufacturers to use agile techniques to increase production performance in real-time operations. In Industry 4.0, sensor data increases transparency across all levels within the manufacturing plant by offering visual depictions of peaks and flows [43]. In addition, intelligent sensors and factory digitalization enable firms to retain open, dependable, and high-quality production. For instance, data-driven strategies and operations increase the quality of products and allow companies to produce individualized products that meet customers' particular needs [51,52]. This increased customization enhances organizational competitiveness within the current global business environment characterized by turbulent changes and uncertainties. Moreover, manufacturers leveraging smart sensor technologies are more compliant and efficient in improving production performance as a result of greater precision in the plant. Javaid et al. [4] summarize the importance of sensors in enhancing performance by indicating that the future of intelligent production involves merging physical and cyber technologies to create a digitally linked manufacturing facility. Thus, Industry 4.0 integrates discrete structures and uses the capability of huge data volumes facilitated by sensor technologies, among other innovations, to boost automation.

4.4.3. Monitoring the Manufacturing Process

In the manufacturing industry, sensors are utilized to track the whole process. These are used to collect and transmit data to central cloud computing platforms to collect and analyze Industry 4.0 data [43]. Intelligent sensors are also valuable for a variety of sectors. In medicine, they evaluate biological activities such as blood flow during surgery. Architecture, engineering, and construction monitor heat leaks in structures and industrial plant buildings [53]. In retail, sensors are employed for sensing client positions and tracking crowd movement. Various retail businesses also utilize this technology to pinch consumers' cell phones and coupons for brand discounts on the perimeter of their stores.

4.4.4. Sensors Are Used To Regulate Processes

Numerous sensors are critical in tracking and regulating an organization's activities that leverage emerging technologies. For instance, hundreds of sensors are deployed in IoT-enabled sectors to strengthen industrial control due to their remote sensing and tracking capabilities [54]. For example, wireless sensors monitor and adjust business processes, enhance connectivity, and provide real-time insights [53]. Manufacturing lines increasingly rely on sensors for product development solutions since they help detect material movement as part of tailored automation. In addition, traditional conveyor manufacturers include long-distance sensors in their systems to expand production automation possibilities without interruption due to closeness [55]. These aspects illustrate the diversity of sensor capabilities that help manufacturers and other businesses integrate sensor technologies into their ICT infrastructure to monitor and regulate their business operations.

4.4.5. Sensors Play Critical Roles in Information Gathering and Transfer

The ongoing digital transformation is data-driven, where companies collect and analyze vast amounts of data to make informed decisions. This situation illustrates the significance of sensors throughout this revolution since they are designed to collect and transfer information. Intelligent sensors can accumulate vast data [56]. For example, they can detect temperature, humidity, stress, pressure, colour, light, inconsistencies, and other factors that affect the manufacturing process depending on their configuration [43,57]. They are linked with gateways that enable them to send this captured data to the cloud server. In addition, sensors may be used as part of an IoT network to monitor the environment for delicate devices, drug temperatures, and the development of bacterial food.

4.4.6. Sensors Enhance Quality Management

Modern manufacturing may utilize sensors to help with quality management and monitoring on equipment platforms. Potential manufacturers are finding the advancements in sensor technology to help increase efficiency, thus making them essential [58]. For instance, intelligent sensors connect diverse operating systems, allowing different devices to interact and make intelligent decisions. These smart sensors use microprocessors to personalize outputs and interpret insights while ensuring accurate performance compared to traditional, old-fashioned sensors [53]. Given the rapidly changing customer needs and the competition in the global markets, customization has become a critical differentiation element for companies aiming to maintain a profitable consumer base. Unlike in the past, where large companies competed for international markets, globalization and advanced technologies have opened these markets to other smaller players, including SMEs that previously focused on domestic markets [59,60]. Therefore, organizational management is leveraging reliable data and effective machine-to-machine communication to make informed decisions regarding their operations and enhance their competitive edge.

4.5. Challenges in Sensor Technologies

Despite the numerous benefits and opportunities sensor technologies create, they are affected by various challenges that undermine their adoption and maximum performance. For instance, Varshney et al. [3] indicate that the probability of signal delays and loss is expected with wireless sensors. This is mainly because these sensors are often deployed in hostile and challenging environments such as space and meteorology applications, biomedical measurements, physical and chemical metrology, and electrical and electronic measurements [3] (p.223). Other challenges related to conceptualization and optimization include tracking, reliability, and coverage. For example, issues with the programming model for the sensing network can undermine the quality of sensor services, including the measurements and the data output transferred [43]. Consequently, these issues can lead

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to more severe problems, such as wrong decisions based on inaccurate insights and the inability to detect threats on time. Therefore, there is a need to develop reliable sensor networks that do not subject users and their operations to any potential hazards.

Like other Industry 4.0 technologies, sensors are prone to attacks. According to Varshney et al. [3], a wormhole poses a critical threat to wireless sensors. This threat occurs when an attacker creates dangerous nodes and leverages the false routes it generates to manipulate the systems. The MAC centralized routing protocol (MCRP) is suggested as a practical solution to keeping communication links safe. However, the increased cyber threats and attacks reflect the need for further advancements and investments in security frameworks to strengthen the safety of all interconnected machines and systems in Industry 4.0 [42]. Another challenge in leveraging sensor technologies and promoting digital transformation is the reluctance to share information among business partners. Some competitors fear sharing information can empower their rivals, reducing their competitive edge [58]. In addition, information sharing is affected by multiple legal and ethical issues related to violating consumer privacy. These issues create fear and a lack of trust, resulting in the slow adoption of advanced technologies in various sectors.

5. Conclusions

Industry 4.0 is associated with massive digital transformation facilitated by adopting emerging advanced technologies such as Cloud Computing (CC), the Internet of Things (IoT), Big Data, digital twin, and Additive Manufacturing. Factors such as changing consumer needs, short product life, and increasing operational costs are critical drivers toward digitalization as companies embrace these technologies to exploit their benefits. For instance, Industry 4.0 is characterized by interlinked networks and devices, thus enhancing communication, information transfer, and operational efficiencies. In addition, data-driven technologies improve automation and reduce human errors in the manufacturing process. However, successfully exploiting these innovations requires integrating sensor technologies throughout various points in the advanced ICT infrastructure. The findings presented in this paper indicate that sensors are used to connect multiple systems and devices, thus enabling machine-to-machine communication. In addition, smart sensors are critical data collection tools since they are used to detect input data such as heat, light, motion, and pressure. These data allow operators to monitor equipment and processes.

Sensor technologies in Industry 4.0 are associated with multiple benefits and applications. For instance, sensors improve production performance by increasing real-time transparency and visualization of operations. As a result, manufacturers can monitor peaks and flows and use the information gathered to implement improvement strategies. In addition, sensors facilitate great precision during product designing, development, and production, thus enabling customization and improving quality. With intelligent sensors integrated into diverse operating systems, it has become easier for manufacturers to increase efficiency as they exploit reliable data and effective machine-to-machine communication. However, despite these benefits, the current sensor technologies face multiple challenges that undermine their maximum adoption. For instance, deploying wireless sensors in hostile and challenging conditions can result in signal delays and loss, raising concerns over reliability and coverage. Some manufacturers also fear that potential issues in their programming models can lead to severe problems, such as data inaccuracy and misleading insights, that may cause huge losses and threaten the systems. Moreover, sensors are prone to cyber-attacks and can lead to extreme security and privacy issues resulting in lost trust and confidence in the company among customers. Therefore, while the current sensor technologies are promising, further developments are required to address these issues and potentially increase their adoption.

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Appendix A

Table A1. Overview of document citations period 2012 to 2022.

Documents		2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total
Graph Neural Networks for Anomaly Detection in Industrial In ...	2022	-	-	-	-	-	-	-	-	-	-	15	18
Fourth Industrial Revolution between Knowledge Management an ...	2022	-	-	-	-	-	-	-	-	-	-	3	3
Analyzing the Levei of Digitalization among the Enterprises ...	2022	-	-	-	-	-	-	-	-	-	-	4	5
Digital Twins: A Survey on Enabling Technologies, Challenges ...	2022	-	-	-	-	-	-	-	-	-	-	3	3
Food traceability 4.0 as part of the fourth industrial revol. ..	2022	-	-	-	-	-	-	-	-	-	-	4	4
The fourth industrial revolution in the food industry-Part 1 ...	2022	-	-	-	-	-	-	-	-	-	-	20	22
Digital Transformation of a Production Line: Network Design, ...	2022	-	-	-	-	-	-	-	-	-	-	6	6
Digital Retrofitting of legacy machines: A holistic procedur ...	2022	-	-	-	-	-	-	-	-	-	-	1	1
Towards a data science platform for improving SME collaborat...	2022	-	-	-	-	-	-	-	-	-	-	11	12
Towards Industry 4.0: Digital transformation of traditional ...	2021	-	-	-	-	-	-	-	-	-	-	1	1
Long-term wireless sensor network deployments in industry an ...	2021	-	-	-	-	-	-	-	-	-	-	2	2
Integration of ontologies to support Contrai as a Service in ...	2021	-	-	-	-	-	-	-	-	-	1	3	4
Theory and practice of implementing a successful enterprise ...	2021	-	-	-	-	-	-	-	-	-	-	3	3
Human centric digital transformation and operator 4.0 for th ...	2021	-	-	-	-	-	-	-	-	-	-	4	4
Industry4.0: Advanced digital solutions implemented on a cl ...	2021	-	-	-	-	-	-	-	-	-	2	2	4
Industry4.0 Model for circular economy and cleaner producti ...	2020	-	-	-	-	-	-	-	-	1	25	29	55
Drilling in the Fourth Industrial Revolution-Vision and Chal ...	2020	-	-	-	-	-	-	-	-	2	14	6	23

Comparison of 5G enabled control loops for production	2020	-	-	-	-	-	-	-	-	-	5	3	8
Enhancing Cognition for Digital Twins	2020	-	-	-	-	-	-	-	-	-	3	7	10
A Measurement lnformation lnfrastructure's Benefits for lndu ...	2020	-	-	-	-	-	-	-	-	-	6	2	8
A framework for sustainable and data-driven smart campus	2020	-	-	-	-	-	-	-	-	-	2	2	4
Development of a Predictive Maintenance 4.0 Platform: Enhanc ...	2020	-	-	-	-	-	-	-	-	-	5	1	6
Smart Factory Competitiveness Based on Real Time Monitoring ...	2020	-	-	-	-	-	-	-	-	-	2	2	4
llot platform for agile manufacturing in plastic and rubber ...	2020	-	-	-	-	-	-	-	-	-	1	1	2
loT-CryptoDiet: lmplementing a lightweight cryptographic lib ...	2020	-	-	-	-	-	-	-	-	-	1	1	2
loT and Big Data Analytics for Smart Buildings: A Survey	2020	-	-	-	-	-	-	-	-	6	20	25	52
Getting small medi um enterprises started on industry 4.0 usi ...	2020	-	-	-	-	-	-	-	-	1	4	2	7
loT-enabled smart appliances under industry 4.0: A case stud ...	2020	-	-	-	-	-	-	-	-	18	56	50	127
Metrology for the factory of the future: Towards a case stud ...	2019	-	-	-	-	-	-	-	-	6	7	2	15
Towards an energy management system transformation in an ind ...	2019	-	-	-	-	-	-	-	-	2	-	-	2
A Meta-Model of Cyber-Physical-Social System: The CPSS Parad ...	2019	-	-	-	-	-	-	-	-	2	4	3	9
The Industrial Internet ofThings: Examining How the lloT Wi ...	2019	-	-	-	-	-	-	-	1	4	10	3	19
Digital twin bridging intelligence among man, machine and en ...	2018	-	-	-	-	-	-	-	4	6	2	5	17
Applying value proposition design for developing smart servi ...	2018	-	-	-	-	-	-	1	4	6	2	4	17
1ndustry 4.0 urban mobility: goNpark smart parking tracking ...	2017	-	-	-	-	-	-	1	4	-	4	-	9
Pattern extraction for the design of predictive models in in ...	2017	-	-	-	-	-	-	1	12	10	4	2	29
	Total	-	-	-	-	-	-	3	25	64	183	232	517

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