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Sustainability in the Civil Construction Sector Supported by Industry 4.0 Technologies: Challenges and Opportunities †

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Abstract: The civil construction sector is under pressure to make construction processes more sustainable, that is, aligned with economic, social, and environmental sustainability. Thus, the research question considers: How do Industry 4.0 Technologies help civil construction face challenges and identify new opportunities to become sustainable? The general objective of this work is to offer a current overview of publications that associate the civil construction sector; Industry 4.0 Technologies and sustainability, and identify the challenges and opportunities of the Industry 4.0 Technologies set to contribute to sustainability achievement. The research method was a bibliographic review combined with bibliometric analysis in SCOPUS databases. The results show that civil construction faces the challenge of reducing the consumption of natural resources, ensuring safe work, and optimizing processes, especially handwork. However, the insertion of Industry 4.0 Technologies into civil construction has allowed sensors, robots, modelling and simulation systems, artificial intelligence, and drones to have their productivity, efficiency, safety, strategic and environmental management enhanced. Furthermore, Industry 4.0 Technologies can contribute to civil construction through innovative, sustainable, and technological solutions focused on the flow of work, which can provide growth through the balance of costs/benefits in the management of projects and works. Thus, it is expected that this article will contribute to discussions around the possibility of construction becoming sustainable with the support of Industry 4.0 Technologies.

Keywords: technologies 4.0; sustainable construction; construction industry challenges; construction industry opportunities; sustainability; construction 4.0; intelligent construction; sustainability; industry 4.0; sustainable construction processes

1. Introduction

According to Lezoche et al. [1], the historical evolution of industry is marked by four phases, the first of which is referred to as the First Industrial Revolution, with the advent of steam machines and the use of coal as fuel. The Second Industrial Revolution stood out for the emergence of electric power and serial production lines. The Third Industrial Revolution provided automation of machines, computers, and the Internet. Currently, the Fourth Industrial Revolution highlights the most abrupt change, where the concept of digitalization and the virtual world are responsible for technologically innovating the production processes. Figure 1 shows the evolutionary phases of the industry, from 1.0 to 4.0.

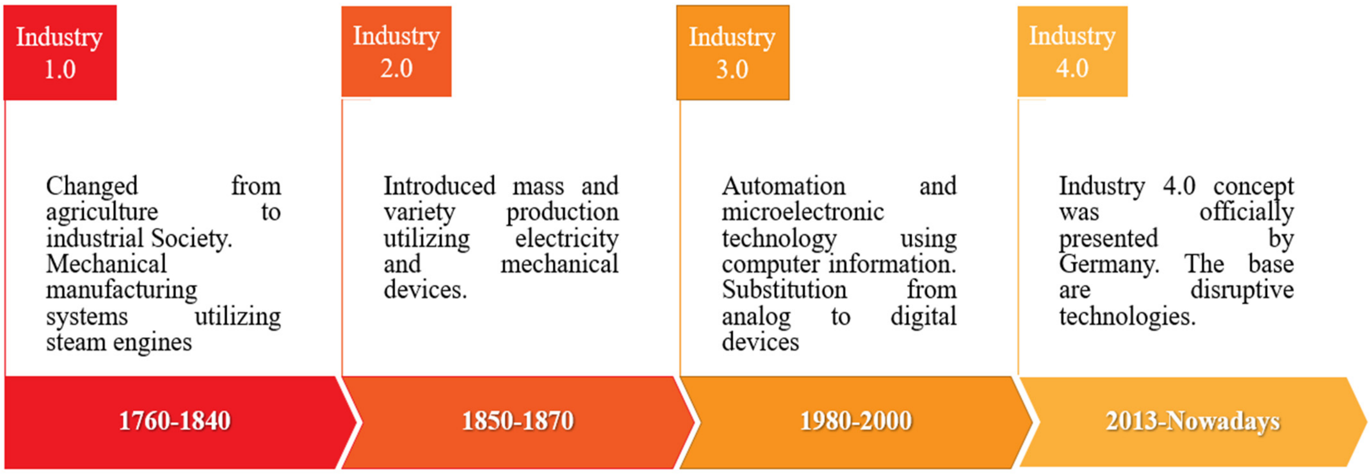

Figure 1. The Evolution from Industry 1.0 to 4.0. Source: Adapted from [2,3].

Industry 4.0 appeared for the first time in 2011 in Germany and is referred to as the fourth industrial revolution [4]. This concept aims to integrate technologies such as the Internet of Things (IoT), Industrial Internet of Things (IoT), Intelligent Objects, Big Data, Cloud Computing, Artificial Intelligence, 3D printing, Sensors, Actuators, Virtual and Augmented Reality [2,5] to create an environment of digital and intelligent manufacturing. Thus, the goal is to use these technologies to generate efficiency and optimize production processes continuously and upwardly by generating greater productivity, quality, and customization. The rapid advance in technological innovations in sensors, devices, information networks, and machine learning has helped robotics and automation progress rapidly, bringing improvements in several productive sectors [5]. In early 2020, during the COVID-19 pandemic [6] in Brazil, according to Zhou et al. [7] the use of technologies has shown its importance using Big Data in Geographic Information Systems (G.I.S.). Mainly regarding rapid visualization of information on epidemics, tracking of confirmed cases, transmission forecast, balance and management of supply and demand of material resources [8] and the use of artificial intelligence (A.I.) to identify the transmissibility of the virus, populations at risk, and thus the ability to establish the infection cycle and suggest effective and preventative control measures [9].

All productive sectors are under pressure to develop their activities sustainably, based on environmental, social, and economic pillars, to promote the future of current and new generations. The continuous growth of cities and society elicits various concerns for improved development and management of the multifaceted urban systems, including resilience and sustainability [10]. Thus, considering these new scenarios and paradigms, the civil construction sector stands out, which is still regarded as unsustainable when employing archaic processes and activities, collection procedures, data recording, less automated and incomplete monitoring that results in waste of materials and exacerbated use of natural resources, beyond the unavailability of qualified labor [11].

However, sustainability was defined in the World Commission on Environment and Development's 1987 Brundtland report 'Our Common Future' as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' [12]. Since then, industries and business have also become part of the search for the sustainability of operations so that they can remain profitable and positively impact society and with concern about the environment's ability to regenerate, thus, the American businessman Elkington, defines the Triple Bottom Line (TBL) concept determining three pillars: economic, social and environmental with a focus on the business perspective [13]. The implementation of the Sustainable Development Goals (S.D.G.s) since 2016, is strengthened through the S.D.G. 9—Industry, Innovation and Infrastructure, civil construction to actively participate in this universal call, in search of sustainable development, which contributes to a change in business and construction models supported by people and technologies [14]. This new model supported by construction, society and environment contributes to the attainment of the seventeen goals proposed by the U.N., since it affects the entire supply chain and brings improvements in resource efficiency, error elimination, reduction in waste of materials, energy and transportation (S.D.G. 7; S.D.G. 14; S.D.G. 15), as well as help achieve poverty eradication (S.D.G. 1) and zero hunger (S.D.G. 2), good health and well-being (S.D.G. 3), gender equality (S.D.G. 5), clean water and sanitation (S.D.G. 6), decent work and economic growth (S.D.G. 8), reduction inequalities (S.D.G. 10), sustainable cities and communities (S.D.G. 11), responsible consumption and production (S.D.G. 12) and direct actions against global climate change (S.D.G. 13) [11].

Some review articles related to the Civil Construction and Industry 4.0 Technologies were published. However, the review scopes are concentrated in just one industry technology 4.0, such as patterns and trends IoT by Ghosh et al. [15], extrusion-based additive manufacturing with 3D printing analyzed by Valente et al. [16], Sepasgozar [17] studied the Digital Twin application to expedite a smart and sustainable built environment, Darko et al. [18] explored Building information modelling (BIM) and appointed the survey and future needs, and Zhang et al. [19] identified Virtual reality applications for the built environment. Furthermore, the implications for the sustainability pillars are not the main research focus, thus there is a gap regarding the Industry 4.0 Technologies main contributions to the Triple Bottom Line. Although these studies contributed to the state of the art in Civil Construction and Industry 4.0 Technologies, this paper adds to these previous reviews the systematization of the Industry 4.0 Technologies set that can help us to face current civil construction challenges and contribute to the identification of opportunities through practical examples in order to permit the sector to achieve sustainability.

Along these lines, discussions aimed at improving production patterns and using resources through new approaches, practices and innovative technologies that enable the construction sector to develop in a structured and sustainable way become essential. Construction 4.0 presents a promising initiative that helps other industrial sectors improve productivity indicators by optimizing operational processes using innovative technologies. Thus, the general objective of this work is to offer a current overview of publications that associate the civil construction sector; Industry 4.0 Technologies and sustainability and identify the challenges and opportunities of Industry 4.0 Technologies set to contribute to sustainability achievement. After this introduction, the paper is structured into five additional sections. Section 2 presents the literature review. Section 3 presents the research methodology. Section 4 presents the bibliometric results. Section 5 presents the discussion and systematizes the challenges and opportunities through a table and, finally, Section 6 presents the final considerations.

2. Literature Review

Construction 4.0 is the application of the concepts of Industry 4.0 in the construction sector, that is, the application of digital technologies and processes adapted to the construction environment [20]. Construction represents one of the largest industries in the world, which contributes to around 13 percent of the global gross domestic product (GDP) [16]. In Brazil, the forecast of the civil construction sector's gross domestic product (GDP) is expected to increase by over 22 percent until 2025 [21]. However, this sector is responsible for the use of scarce natural resources [15], exacerbation of fossil energy source use even considering its limitation and delivery capacity [22]; increasing greenhouse gas emissions and global warming at large [23], energy consumption [17] generation of big quantities of solid wastes which are difficult to apply to waste management [24], and low use of technologies [25].

An abundance of research activity has been conducted to optimize civil construction utilizing Industry 4.0 Technologies, but review studies available on the topics are limited in terms of examples of using technologies and their final applications, and, mainly, in terms of the implications for the sustainability of the construction industry. Relevant studies review the use of only one technology in construction, such as IoT [15], 3D printing [26–28] and Virtual and Augmented Reality [19,27]. Others have reviewed a joint application of technologies such as BIM and IoT [17], Blockchain and BIM together in disaster recovery of buildings [29], or application of BIM to applications under construction in forum sites [30]. None of these studies present detailed discussions on the environmental, social and economic impacts of adopting new technologies in operations.

Nevertheless, some studies have comprehensively revealed the application of Industry 4.0 Technologies in construction [31–33]. However, these studies also have a limited scope in terms of Triple Bottom Line contemplate [33] which reviews the implications of adopting smart technologies for sustainable construction and the positive consequences for health, safety, and the environment. These analyses are restricted to operations carried out on site, that is, while the construction project is being carried out.

Thus, it is noted that the implications for sustainability are not the main target of the reviews conducted so far. Despite the growing interest in the application of Industry 4.0 Technologies in construction, there is a knowledge gap regarding contributions to the sustainability dimensions of the adoption of such technologies in the construction production chain [34]. The researchers are more focused on the technical aspects of [31]. Environmental, social, socio-cultural and ethical issues are yet under explored in research relating to the adoption of Industry 4.0 Technologies in civil construction [32].

3. Research Methodology

To understand state of the art, identify knowledge and possible research gaps, the research method employed was an exploratory bibliographic review combined with bibliometric analysis [35]. To ensure transparency and traceability of the results reported here, the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) protocol [36,37] was implemented to conduct the research. Figure 2 presents the diagram with the literature review flow; the diagram model was adapted from [38]. The research was carried out on the SCOPUS database in February 2022, using the title, abstract and keyword options, applying the following query and boolean operators:

(1) "CONSTRUCTION" OR "CIVIL CONSTRUCTION" OR "CONSTRUCTION TECHNOLOGY" OR "CONSTRUCTION 4.0" OR "INTELLIGENT CONSTRUCTION" AND;
(2) "TECHNOLOGIES 4.0" OR "INDUSTRIES 4.0" OR "INDUSTRY 4. 0" OR "THE 4th INDUSTRIAL REVOLUTION" OR "THE FOURTH INDUSTRIAL REVOLUTION" AND;
(3) "SUSTAINABLE" OR "SUSTAINABILITY" OR "TRIPLE BOTTOM LINE" OR "SUSTAINABLE DEVELOPMENT".

The approach has a qualitative character since it aims to deepen the knowledge on how the fourth industrial revolution can contribute to advances in civil construction. Table 1 show the inclusion and exclusion criteria applied on SCOPUS database.

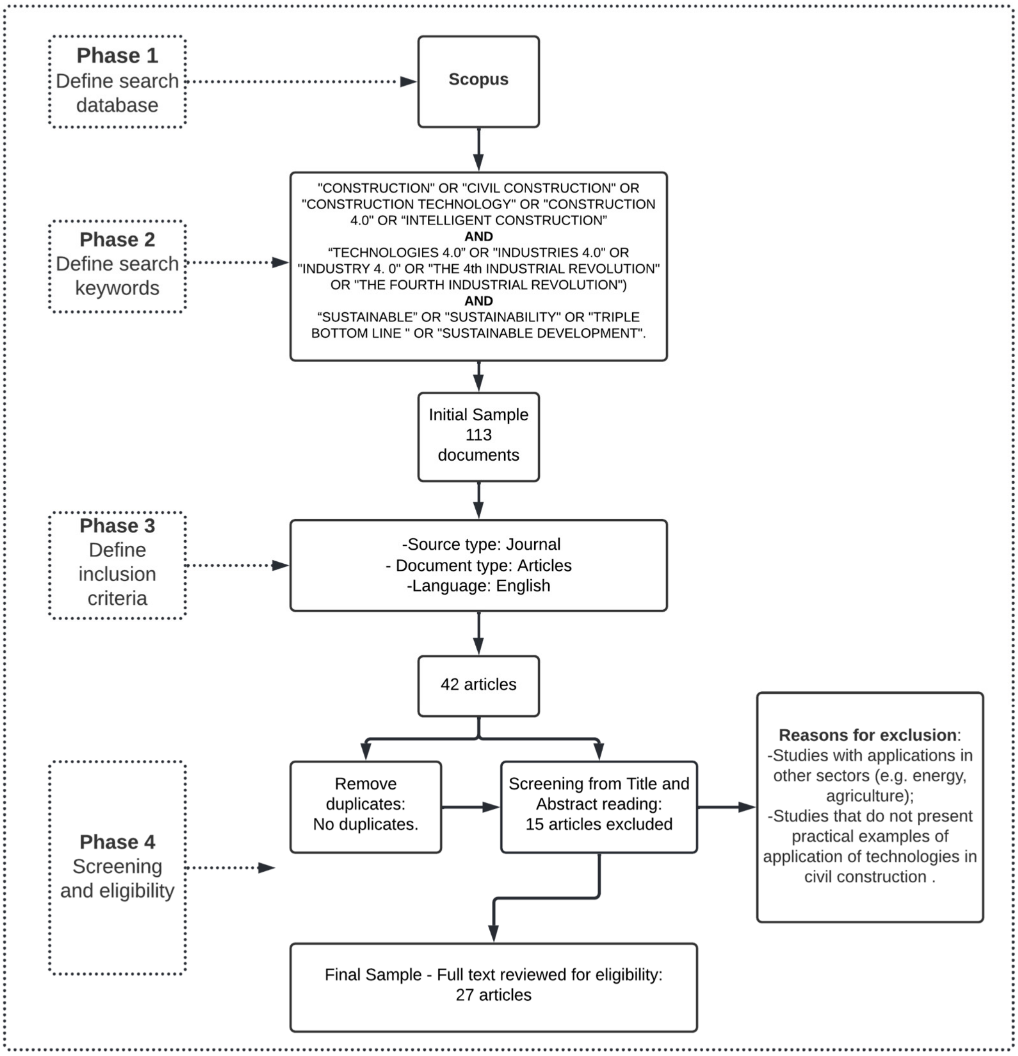

Figure 2. Literature review process flow diagram. Source: Adapted from [38].

Table 1. Inclusion and Exclusion Criteria.

Search Criteria	Inclusion Criteria	Exclusion Criteria
Database	SCOPUS	Other databases
Topic	Title, abstract and keywords	Words that were not present in the title, abstract and keywords
Publication Period	Without restriction	Without restriction
Document Type	Articles	Other documents
Publication Stage	Without restriction	Without restriction
Source	Journals	Books and Conferences
Language	English	Other languages

4. Results

The search returned 113 publications, and after applying the filter, applications resulted in 42 articles and after reading and reviewing, 27 articles fell within the research, which were submitted to a systematic and bibliometric analysis through the VOSviewer software. There has been an evolution of the subject over the last few years, but few publications on the SCOPUS platform have addressed the specific keywords. The search covers articles published in journals peer reviewed between the years 2017 and 2022, before that, there were only two papers published in 2016 at conferences proceedings. There is an increasing trend in the number of publications over the last years, especially from 2021, increasing exponentially, with 69.2% of articles being published only in the previous year. The analysis of the publications' distribution per year on the Table 2 reveals that the interest in adopting Industry 4.0 Technologies in construction has emerged within the last five years, being still a developing topic, with few theoretical and empirical investigations.

Table 2. Bibliographic Analysis Review.

Number of Articles	Authorship	Year	Country	Title	Technologies 4.0 Applied in Civil Construction
1	[39]	2022	Poland	Digitization in the Design and Construction Industry-Remote Work in the Context of Sustainability: A Study from Poland	Digitalization of services (remote work)
2	[40]	2021	Australia	Adoption of blockchain technology through digital twins in the construction industry 4.0: A PESTELS approach	Blockchain/Digital Twins
3	[41]	2021	Australia	Project data categorization, adoption factors, and non-functional requirements for blockchain based digital twins in the construction industry 4.0	Blockchain/Digital Twins
4	[42]	2021	Slovakia	Simulation modeling of aerial work completed by helicopters in the construction industry focused on weather conditions	Digital Simulation Model
5	[43]	2021	Spain	Circular economy in the building and construction sector: A scientific evolution analysis	Building Information Modeling (BIM)
6	[44]	2021	Hungary	Construction 4.0 organizational level challenges and solutions	Augmented and Virtual Reality
7	[35]	2021	China	Understanding digital transformation in advanced manufacturing and engineering: A bibliometric analysis, topic modeling and research trend discovery	BIM/Digital Twins/Additive Manufacturing (3D)

Table 2. *Cont.*

Number of Articles	Authorship	Year	Country	Title	Technologies 4.0 Applied in Civil Construction
8	[45]	2021	South Korea	The engineering machine-learning automation platform (Emap): A big-data-driven AI tool for contractors' sustainable management solutions for plant projects	Artificial Intelligence (Machine Learning)/Big Data
9	[46]	2021	Czech Republic	Safety of construction from the point of view of population protection in the context of industry 4.0 in the Czech Republic	BIM
10	[28]	2021	Italy	Building envelope prefabricated with 3D printing technology	3D printing for prefabricated components to building
11	[47]	2021	Poland	Global water crisis: Concept of a new interactive shower panel based on IoT and cloud computing for rational water consumption	IoT and cloud computing
12	[48]	2021	Italy	Smart green prefabrication: Sustainability performances of industrialized building technologies	Premanufactured Building Technologies
13	[49]	2021	Nigeria	The disruptive adaptations of construction 4.0 and industry 4.0 as a pathway to a sustainable innovation and inclusive industrial technological development	All 4.0 Technologies
14	[50]	2021	United Kingdom	Distributed manufacturing: A new digital framework for sustainable modular construction	Modular building construction (Premanufactured); IoT; BIM; Advances in Materials
15	[51]	2021	Malaysia	Assessing predicting factors: Good management practices towards the successful implementation of green supply chain management (gscm) in IBS construction project	Industrialized Building System (IBS) and Digitalization

Table 2. *Cont.*

Number of Articles	Authorship	Year	Country	Title	Technologies 4.0 Applied in Civil Construction
16	[52]	2021	United Arab Emirates	Construction Industry 4.0 and Sustainability: An Enabling Framework	Building information modeling and automation vis-à-vis others such as cyber–physical systems and smart materials, with significant growth expected in the future for blockchain- and three-dimensional-printing-related technologies.
17	[53]	2021	Nigeria/South Africa	Effect of the Fourth Industrial Revolution on Road Transport Asset Management Practice in Nigeria	robotics, mobility, virtual and augmented reality, Internet of things and cloud computing, machine learning, artificial intelligence, blockchain, three-dimensional (3D) printing drones and digital engineering.
18	[54]	2021	South Africa	3D printing for sustainable low-income housing in South Africa: A case for the urban poor	three-dimensional (3D) printing), factor analysis aided by 3D printing technology, accessibility of technology
19	[55]	2021	India	Actionable strategy framework for digital transformation in AECO industry	Three-dimensional (3D) scanning, BIM, Drones/Augmented Reality/IOT/Machine Learning/Cloud Computing/Big Data/Sensors
20	[56]	2020	Spain	Skill needs of the civil engineering sector in the European Union countries: Current situation and future trends	(BIM), the Internet of Things (IoT), 3D laser scanning and component printing, big data analytics, augmented reality (AR), robotic construction, artificial intelligence (AI), sensor systems, intelligent materials, drones
21	[57]	2020	Cyprus (First author)	Building information modeling applications in smart buildings: From design to commissioning and beyond A critical review	BIM/ IOT (and digital design techniques, research in building design and optimization, BIM and LCA monitoring and tools)
22	[58]	2020	Australia	Criteria development for sustainable construction manufacturing in Construction Industry 4.0: Theoretical and laboratory investigations	Three-dimensional (3D) printing construction, software Strand7 Finite Element Analysis, Physical and mechanical properties of samples

Table 2. *Cont.*

Number of Articles	Authorship	Year	Country	Title	Technologies 4.0 Applied in Civil Construction
23	[59]	2020	Malaysia	Integrating building information modeling (BIM) and sustainability to greening existing building: Potentials in Malaysian construction industry	Building Information Modeling (BIM), building lifecycles and technology and digitization in the construction industry.
24	[60]	2020	Nigeria	Disruptive technological innovations in construction field and fourth industrial revolution intervention in the achievement of the sustainable development goal 9	BIM/Drones/Robots/ Artificial Intelligence
25	[61]	2019	Malaysia	Developing a framework for life cycle assessment of construction materials through building information modeling (BIM)]	BIM
26	[62]	2018	Croatia	Architectural programs as corporate communications platforms	IoT
27	[63]	2017	Italy	Emergency: innovative prefabricated construction components for an eco-solidarity architecture	Printing machine to produce panels prefabricated

Note that most publications are in European and Asian countries, but there are very few articles that relate to construction, sustainability, and technologies 4.0. Thus far, there are no American publications. Among developing countries, including the BRICS members (Brazil, Russia, India, China, and South Africa), only Brazil and Russia have not contributed to the advancement of research in these areas. The lack of financial resources and a proper management system for construction, informal construction, and demolition waste represent the main challenges that developing countries need to face [64,65]. Although there is no Brazilian article that stands out in the analysis, Brazil is still a country that suffers from challenges in sustainable construction, such as lack of more efficient government policies, lack of specialized labor, productivity losses and time with routine construction, problems in the disposal of construction waste and few uses and applicability of technologies 4.0 in favor of sustainable construction [66]. The publication's distribution is presented in Figure 3.

The most relevant publications on the subject are concentrated in articles, representing more than 40.6% of the total published in five years. The main areas of indexation of journals are Engineering with 25.3% of publications; followed by Social Sciences with 18.9%; Environmental Sciences with 13.7%; Energy with 12.6% and 29.5% distributed in small percentages among the other areas. This distribution reveals that the technical and academic areas are the most engaged in the growth process of Industry 4.0 Technologies, aligned with the concepts of sustainability and civil construction.

By using VOSviewer software, based on the network of 27 articles extracted from the SCOPUS database, the keywords density visualization presents the co-occurrence of keywords. The more keywords around the node and the higher their frequency, the deeper the color appears (shown in yellow in Figure 4. It can be seen from the map that the top five keywords with high frequency in the research are: Industry 4.0 (18 times);

Sustainable Development (12 times); Sustainability (13 times); Construction 4.0 (8 times), and Innovation (6 times). At the same time, the others are a subset of it. The analysis of the nodes, which presents the strongest links on the map, reveals that current research aims to use technologies to help construction to achieve higher sustainability standards, thus contributing to sustainable development goals.

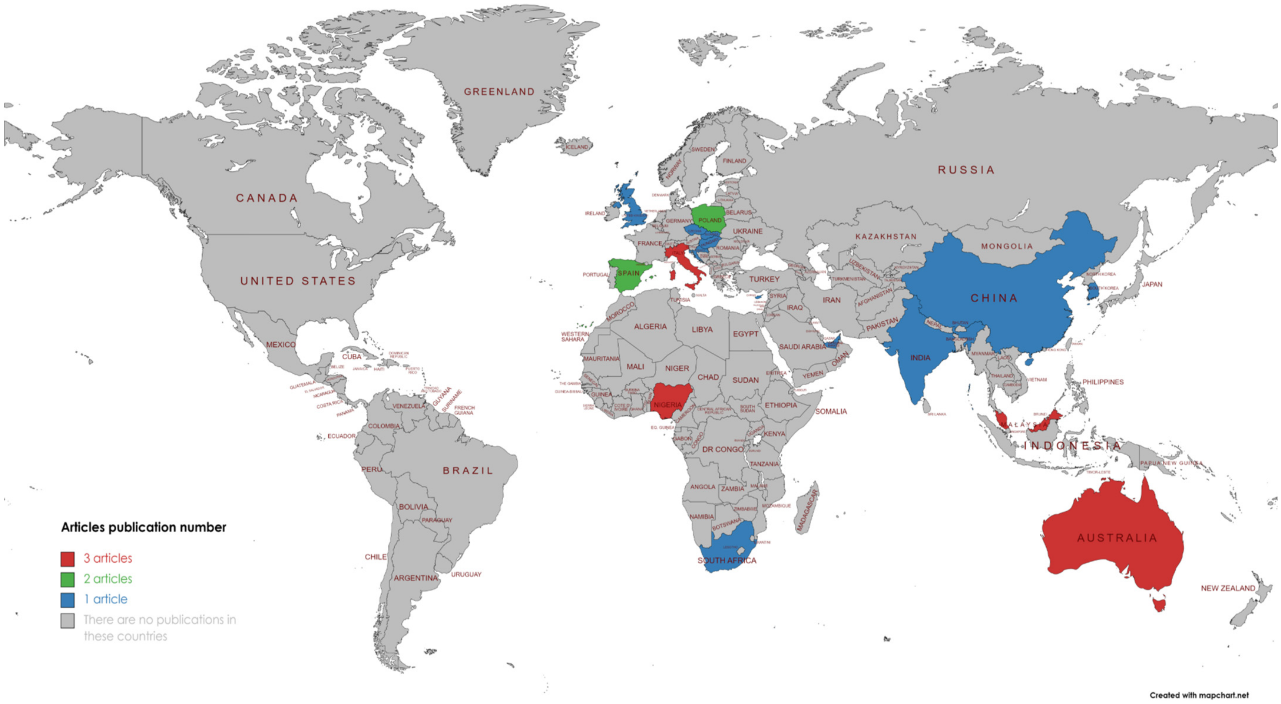

Figure 3. Countries with the highest number of publications in the last five years. Source: Own elaboration supported by MapChart tool, 2021.

Figure 4. Keywords Co-occurrence Density map. Source: Own elaboration supported by VOSviewer, 2021.

The secondary cluster with the higher density is composed of the keywords (innovation and strategic approach and management practice), signaling that the implementation of technologies in construction depends on a new innovative approach in relation to the strategic and operational activities of the construction. This is also reinforced by the proximity to the term (digitalization), the core of the industry 4.0 concept.

There are also weaker links and intensity, these being mainly constituted by keywords related to individual technologies (3D printing; building information modeling; sensor networks) and managerial practices that can operationalize the themes of the central cluster. Technologies that are used together appear close to each other, for example, the terms (Blockchain and IoT) share a strong link since Blockchain technology is being implemented in IoT-enabled digital systems to avoid data and information vulnerability that travels over the Internet. Likewise, the terms (additive manufacturing and 3D printing) are due to 3D printing being the most used technology for additive manufacturing.

In addition, there is a concern with the sustainability of constructions gaining strength through the terms (life cycle analysis and manufacturing and building construction and sensor networks), which also indicates a change in the standard of assessment of environmental impacts in the construction industry, where the use of emissions data and resource consumption are collected with the help of sensors to feed environmental impact assessment systems.

The main result of the bibliometric review presents a description of the applicability of Industry 4.0 Technologies associated with civil construction. As shown in Figure 5, the revolution seen in the construction industry is marked by the adoption of disruptive technologies. In the content analysis of the articles, we identified 15 Industry 4.0 Technologies applied in the Construction. The most investigated technologies in the literature are Building Information Modeling (BIM) and 3D printing and scanning, being analyzed in 12 articles each. Then, IoT and Artificial Intelligence, represent the next most investigated with 7 and 6 articles, respectively. This analysis shows that there are many gaps regarding the implementation and impact of many technologies in the context of construction.

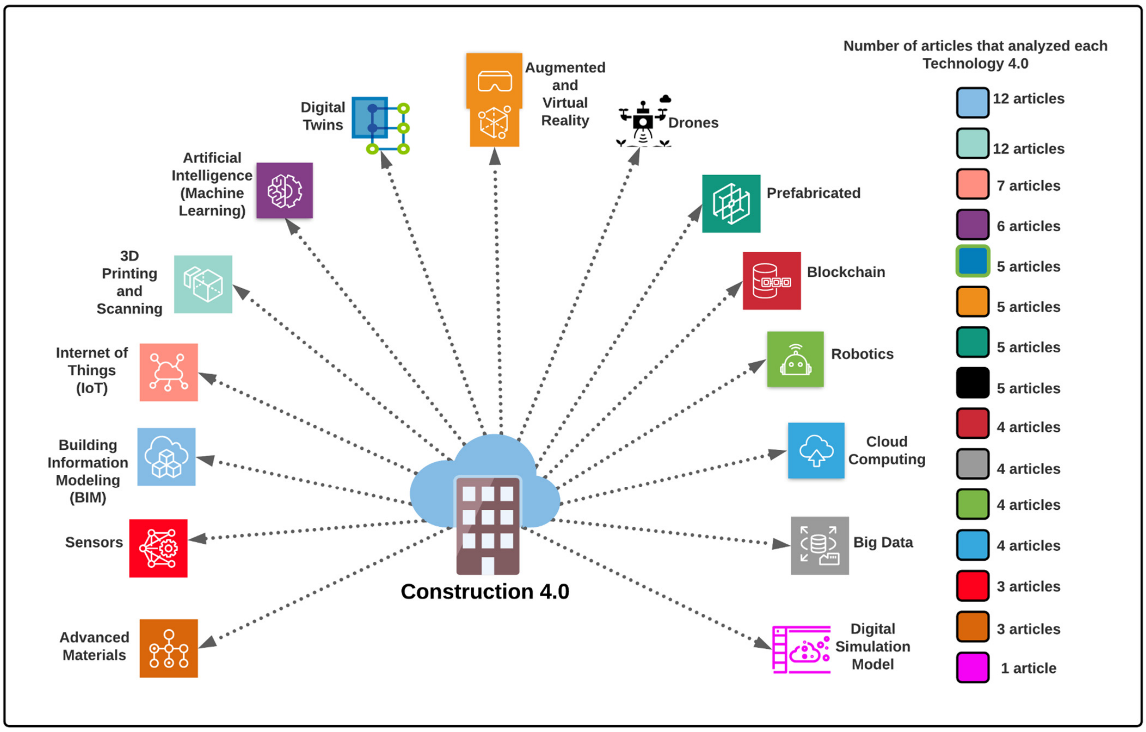

Figure 5. Technological contributions to civil construction. Source: Own elaboration supported by Lucidchart Educational Software, 2021.

5. Discussion

The construction industry plays an essential role in a country's economic growth, mainly in developing countries such as Brazil, where the construction sector represents one of the largest sectors of the global economy, employing about 7% of the population every year [48]. However, civil construction has been criticized for activities and processes that generate a loss of materials, overuse of natural resources, high volumes of waste whilst obstructing achievement of the sustainable development goals (S.D.G.s) goals [67].

In highlighting the civil construction sector, it is necessary to understand that it is an area facing many challenges in maintaining its activities and consequently in achieving sustainable development goals, given that the construction production chain significantly impacts the three pillars of sustainability. Furthermore, construction remains one of the least digitalized and innovative sectors in using Industry 4.0 Technologies. It is only ahead of agriculture, which occupies last place in the McKinsey Global Institute Industry Digitization Index [68]. Although construction is moving towards automation, it still has no links to promising topics such as sustainability [69].

The construction sector bears the highest rates of work accidents worldwide, improving the implementation of technologies can be seen as a social solution to the health and safety of workers [33]. Technologies for information management and visualization are instrumental in enhancing human perceptions and interpretations of complicated project information [70]. Furthermore, an essential contribution of the industry 4.0 technologies use in construction lies in the possibility of automated data collection for environmental impact assessments in a life cycle approach, called Life Cycle Assessment (LCA). In LCA studies, the availability of specific data, inputs and outputs associated with the production of materials, products and processes is a challenge for the execution of reliable studies. The lack of data compromises the quality of the study and the validity of the results found. Thus, [61] propose a framework in which BIM can automate data collection and LCA studies in the context of construction, allowing recognition of the environmental load of materials, processes and operations and direct design improvements to reduce such impacts. Data collection for the LCA is operationalized through the integration of sensors and IoT enabled devices to BIM [57]. Green BIM for environmental sustainability can be used for monitoring and management over a building's full life cycle, and should then be considered in future research [71].

The adoption of Industry 4.0 Technologies can support the construction industry to implement Circular Economy standards and consequently achievement of the S.D.G.s, promoting resource efficiency from project inception to end-of-life. By incorporating circular design requirements into the technologies, such as design for disassembly, deconstruction, and recycling, it is possible to reduce the use of non-renewable natural resources, properly manage the waste stream, and close the materials loop [43,72]. Table 3 systematizes and compares the evolution of methods employed in construction separated by current challenges and opportunities for the main Industry 4.0 Technologies identified in construction.

Table 3. Challenges and Opportunities in the construction sector. Source: elaborated by the authors.

Technology	Challenges	Opportunities Construction Industry 4.0
1. Pre-manufacture Items produced outside the construction site	The use of conventional construction methods is associated with increased costs, incompatibility of skills, loss of productivity, quality, safety and sustainability and an aging workforce that has reached its limits [73]	Prefabricated items generate savings of financial resources and time as they are installed with more agility [74]. Example: Prefabricated houses, where the structures of the houses are built industrially and only assembled on the construction site [75]. In the context of pre-molded materials, the use of Drywall stands out, which are light and versatile plaster partitions with the function of prevention of superstructures in constructions, used in larger scale in Europe and the U.S.A. [74]

Table 3. *Cont.*

Technology	Challenges	Opportunities Construction Industry 4.0
2. Advances in Materials Green materials, nanomaterials, self-cure materials and reuse and recycled materials	Emphasis of the production function in civil construction, mainly concentrated in the use of such products as metallurgical, ferrous, and non-ferrous [76]. Construction and demolition wastes (C.D.W.) are generated at a large scale in the construction sector [77,78]	The changes in materials seek greater strength, greater durability, better appearance, better workability, and molding. Example: Live concrete or self-repairing, a mixture of ingredients that grows and regenerates itself, used to assemble structures in remote areas to fill cracks [79]. Another example is the use of moringa oleifera in wastewater treatment, which allows the kneading of concrete [80]. The replacement of natural aggregates with C.D.W. recycled aggregates in construction materials, such as mortars, has environmental benefits [77,78]
3. 3D Printing Additive manufacturing technique, where the printer adds layer by layer to print walls and other components	Partially digitalized business and company models [81]	Faster construction and assembly with less waste, where the printing is performed on the construction site itself and pre-made parts made of concrete or metals [82]. Examples: The construction of a 1100 m^2 two-story house with one day of printing, two days of assembly and requirement of only three workers [82]. Another example is the manufacture of masks and protective equipment by students from Universidade Estadual Paulista de Guaratinguetá, Ilha Solteira and Tupã during the COVID-19 pandemic [83–85]
4. Exoskeletons Wearable robotic device, which amplifies human strength up to 20 times	The execution of repetitive operations or actions that require excessive effort have always been the main causes of musculoskeletal injuries in people working on production or construction lines [86]	Used to help workers carry heavy materials on the construction site, avoiding physical stress and injuries [87]. Example: The Industry 4.0 Technologies program leads companies to rethink processes and consider human factors, ergonomics, and sustainability. This leads to a new trend, which places workers in a modern intelligent factory, allowing them to take advantage of interconnected tools [88]
5. Drones/UAVs Unmanned, remotely controlled aircraft	Work performed manually and the need to enter confined spaces and high works, two of the most dangerous practices in civil construction [89]	Used for structure construction, mapping, and monitoring. Example: On the construction site, it performs the mapping and topography of areas and soil, together with 3D scanning and photogrammetry, monitors the progress and quality of structures [90]
6. Augmented Reality Virtualization and interaction with the environment	Creating the model of a building has always been a complex task, especially for existing structures, as it has always included the adoption of traditional methods and physical tools for collecting information [91]	Devices allow interaction with the project in an immersive digital structure. Example: Visualization and interaction with the architectural projects before the realization, which allows the correction of errors. Use of augmented reality glasses to detect defects in constructions [73]
7. Big Data Collection and storage of large amount of construction data	The use of Big Data, marked the dematerialization of information and separates it from its physical carriers, storage, transmission, and processing equipment [92]	Collection of data from works to retain knowledge and assist in future works. Example: Access to Google and NASA Earth Exchange Climate Data Centers, Satellite Images and Weather Information, Ground, Water and Geospatial Data from the Resource Conservation Service for planning and control during the project creation phase [1]

Table 3. *Cont.*

Technology	Challenges	Opportunities Construction Industry 4.0
8. Internet of Things (IoT) Connects all objects present in the environment and transmits data in real time through wireless sensors	Previous global technologies are marked by the widespread adoption of mobile devices connected to the "common Internet" without interconnectivity between devices [93]	It allows the connection and collection of information of the machines, materials, vehicles, and people present on the construction site, in real time. Example: Monitoring of delivery trucks in real time, so that the site is properly and promptly prepared to receive the resources, without harming the flow [94]. IoT can also guarantee the quality of the concrete, where sensors connected to smartphones are linked to the reinforcement and warn when the material has reached a reliable resistance level [95]
9. Sensors Installed in numerous objects to allow the capture of information and the implementation of corrective actions	The analysis was based on the tactile–visual contact, that is, the method of execution through simple probing [96]	Traceability of materials since each tool present in the work has an identity. Together with the Internet of things, they can collect information and make corrective actions in real time. Example: Using digital maps to obtain general information about the terrain through high-definition cameras with sensors mounted on drones to explore specific areas [68]. The Edge, one of the most sustainable buildings in the world, uses sensors to manage the lighting system, which allows it to manage the energy generated and adapt the lighting and air ventilation according to the internal use [97]
10. Artificial Intelligence (AI) Computers learn and recognize events, capture, and share information in real time	It is difficult to control the processes on the construction site efficiently because there was no integrated way to verify information about people, materials and equipment in real time to perform corrective actions [82]	A.I. can monitor hundreds of activities simultaneously on the construction site by monitoring and detecting irregularities. Example: Monitoring schedules, costs, safety risks, warning about deviations in schedules, or failure to meet safety standards, which allows quick action to correct the problem [82]
11. Building Information Modeling (BIM) Digital platform that integrates all construction information throughout the life cycle, using various virtualization and simulation technologies	The construction work, besides taking more time, involved complicated processes, such as management, process control and quality control to completion, which generated numerous problems [98]. Besides that, the unforeseen ground conditions are some of the main contributors to construction cost overruns and late completion [99]	It integrates all the projects and all those involved in construction. Example: BIM contains information on geometry, materials, structure, thermal efficiency and energy performance, installations, production costs [100]. Augmented reality can give digital instructions that virtually overlap the workspace, directing the masons, step by step, during the construction process [101]
12. Blockchain A digital ledger system that creates a distributed, immutable storage of data and information on a network	Data and information shared by value chain members across the project lifecycle are fragmented and vulnerable to manipulation, causing inefficiencies and unreliability [41]	Blockchain is a reliable system for information security of shared data with BIM and IoT. Example: Blockchain implementation reduces data fragmentation and increases trust and transparency of contracts and project processes, allowing secure and assertive management of information, which results in increased collaboration and efficiency [41]
13. Digital Twin An exact virtual replica of the environment or a physical object that provides real-time performance data	The lack of structure and poor digitalization in the construction industry makes it difficult to implement technologies that have the power to improve processes throughout the project lifecycle, such as the Digital Twin [41]	Digital Twin benefits the entire project lifecycle by providing real-time monitoring of data. Example: Automated and simultaneous monitoring of progress and compliance with safety and quality specifications, logistics, resource planning and predictive maintenance [41,102]

Practical Implications and Future Directions

The contributions from the abovementioned reinforce the present article on the challenges and opportunities regarding the usage of Industry 4.0 Technologies, which can help the construction sector and bring improvements in sustainability concerning social, economic, and environmental pillars. Moreover, this highlights that the subject needs further attention by the academy, as there remains an extensive effort required in research related to the topic.

After carrying out the bibliographic research, identifying the selected works and developing the bibliometric and content analysis, several issues can be highlighted in relation to the concept of Construction, Industry 4.0 technologies, and Sustainability. The results revealed a growing field of research and trending topics that will gain more relevance. However, they also indicate that individual technologies are not well connected to sustainability initiatives, with a limited number of experts operating somewhat in isolation and who offer single-point solutions, mainly technical solutions, instead of taking an integrated management "holistic" approach necessary to plan new industrial and residential projects around the world.

Despite the contributions, it is understood that there are limitations in our study, since it qualitatively reviews, that is, only subjectively. Our review analysis is limited by search terms applied only in the Scopus database. The use of certain keywords and selection criteria defined in journal articles and in English bears some restrictions, therefore, all literature that includes publications in other languages and other forms of publication are not reflected in this study. While these limitations present useful avenues for future research to explore and expand on the results of this study, future studies may also focus on expanding the keyword set and use other types of publications, databases, and books, even news with ideas and practices that remain out of the analyses. Another important point is the development of empirical research covering different professionals in the civil construction stakeholder chain and at the strategic, tactical, and operational levels. Therefore, we wish to emphasize the lack of studies focusing on or integrating different Industry 4.0 Technologies highlights gaps such as:

1. The publication's analysis distribution per year reveals that the interest in adopting Industry 4.0 Technologies in construction has emerged within the last five years, being still a "hot topic", with few theoretical and empirical investigations;
2. Thus far, there are no American publications. Among developing countries, including the BRICS members (Brazil, Russia, India, China and South Africa), only Brazil and Russia have not contributed to the advancement of research in these areas;
3. Lack the implementation and impact of many technologies in the context of construction;
4. How two or more technologies can be diffused, that is, worked together; or
5. There are still technical challenges related to the integration of different technologies. Future research should investigate the challenges encountered in the joint application of different technologies, both in theory and in practice;
6. Empirical studies with qualitative and quantitative approaches showing the real advances in the applicability of technological tools in construction;
7. The impacts of industry technology 4.0 affect which and how the pillars of sustainability operate;
8. Proposals for models that allow replicability within the topic's construction, technology and sustainability;
9. Most articles explore the relationship between industry 4.0 technologies in construction from an economic and some environmental point of view, however, few also address the social pillar.

The practical implications of the results of the review allow future research efforts/activities in Industry 4.0 Technologies and sustainability in construction to be developed as discussed through this manuscript. The study benefits researchers and professionals in the construction industry. For researchers, the identified gaps reveal areas of high priority for future research, mainly highlighting the need to relate Industry 4.0 Technologies and sustainability of civil construction activities. Moreover, this study can help managers understand the integrations between Construction and Industry 4.0 Technologies to achieve better operational and environmental organizational results. For the construction industry, the study expands knowledge about available technologies and raises awareness of the latest applicability within construction and expands the potential to become a sustainable sector, which ensures good construction practices, is concerned with workers' health and productivity, and additionally preserves the environment and continues growth economically. The study exposes missing gaps from current research: a broader consideration of the construction adjustments needed to accommodate the use of Industry 4.0 Technologies to make the sector more sustainable. Therefore, these gaps in the literature should direct future research to strengthen the use of Industry 4.0 Technologies in construction to contribute to the sustainability and circularity dimensions of the processes. To continue and stimulate discussions, Table 4 displays some positive and negative impacts of the use of Industry 4.0 Technologies in civil construction from the perspective of the Triple Bottom Line, which can serve as inspiration for increasingly comprehensive and in-depth research.

Table 4. Industry 4.0 Technologies Impacts to the Triple Bottom Line. Source: elaborated by the authors.

Industry 4.0 Technologies	Triple Bottom Line		
	Social	**Economic**	**Environmental**
1. Pre-manufacture	Improve health and safety of workers and local community; Access to habitation with low cost [48]	Improve quality, time, and cost, because construction activities are led within controlled environment [48,63]	Prefabricated reduce natural resources use and increase the effectiveness of waste management at the end-of-life, as the disassembly and recovery materials is facilitated; Reducing of local CO_2 emissions, particulate matter and noise [48]
2. Advances in Materials	Income generation for civil construction waste recycling plants and employees so that the material becomes a problem and a sustainable output [102]	The positive uses of solid waste technological treatment are considered beneficial from the economic and environmental point of view and saving the natural resources [24]	
3. 3D Printing	Low-income housing [54]	3D printing allows for mass customization and fast implementation, which can reduce costs [28,58] 3D printing reduces the cost of construction due to zero waste; it uses recycled materials and it decreases the use of transport [56]	Optimization of resources (energy and materials) use and waste management due to the high precision in the use of materials, which does not generate waste, and the incorporation of recycled materials for the deposition in 3D [58]
4. Exoskeletons	Reduction in work accidents and preservation of health and safety [102]	Costs with trained workers and investment in training [102]	Exoskeleton system it is possible to innovate the architectural image, to support an equitable and sustainable development based on the prevention and risk management and extend the useful life cycle of the built environment [103]
5. Drones/UAVs	Lack of regulatory and administrative interventions to guide the UAVs' safe operation on construction sites [104]	Low-cost unmanned aerial system [70]	To obtain data and images from underneath floating buildings, drones can be equipped with cameras and sensors to collect characteristic construction information [105]

Table 4. *Cont.*

Industry 4.0 Technologies	Triple Bottom Line		
	Social	Economic	Environmental
6. Augmented Reality	Training of workers and prevention of occupational risks [56]	Planning of works in the virtual environment, with a preview of the necessary operations and processes, making it possible to correctly dimension and optimize financial resources [106]	Optimizes the use of resources in all phases of the project, from design to use, identifying potential areas for improvement in energy and water consumption, preventing errors and defects through early visualization of events in the virtual environment [107,108]
	Augmented reality or virtual reality can increase customers' understanding the final product early in the design phase, avoiding changes during the project execution and consequently avoiding redesign costs [55]		
7. Big Data	Using big data, information on work progress and suppliers and employees payments are distributed through blockchain-based smart contracts for appropriate project managerial [34] Big Data-generated data in the stages of a project is collected and formalized into a repository to be used as a knowledge base [45]		The use of cloud-based big data enables building sustainability management as a means of predicting, managing, and monitoring the impacts of a building project on the environment [71]
8. Internet of Things (IoT)	IoT maintain safety and health of workers through real-time alerting of potential falls and collisions [109] IoT can monitoring urban places exposed to extreme environmental conditions, as areas subject to flooding and landslides, minimizing or preventing deaths in natural disasters [62]	Automated real-time data collection saves resources as it streamlines the planning, communication, control and optimization of processes, inventories, preventive maintenance, time and budgets [15,110]	Real-time monitoring of parameters on emissions and consumption of resources, such as water and energy, to reducing resource scarcity [47]
9. Sensors	Sensors monitoring health parameters of workers and the environment avoiding ergonomic injuries and release of harmful substances [33].	Due to the wide variety of pollutants in the civil construction, pollutant monitoring technologies should play a significant role in the very near future as the technologies of low cost sensors evolve fast [22]	
10. Artificial Intelligence (AI)	A challenge for the current management model, such as the replacement of manual activities with digital activities, also continuous workers and knowledge transfer from other sectors [44]	Artificial Intelligence can predict and respond to potential risks in a construction project cycle, reducing design changes and rework predicts, design cost estimating, design error check, change in order forecast, and predictive maintenance, bringing potential environmental benefits by optimizing the use of resources [45]	
11. Building Information Modeling (BIM)	Monitoring health and safety issues—reduction of work accidents. The BIM are able automatically detect safety hazards and suggest preventive actions to workers [57] Population protection requirements can be incorporated in the information modeling system, helping to choose places safe and sustainable to build [46]	BIM increasing productivity and efficiency of operations and process; Decrease of time execution and improve quality of the projects [60] BIM can provide accurate statistics, facilitating cost estimation, construction schedule control and provide spatial and time information [15].	The use of BIM models contributes to assess and improve: energy performance; CO_2 emissions; resource efficiency and waste management; air quality [57] Use BIM to improve design from the projects conception, for example, design for disassembly and deconstruction, contributes to reduce the use of resources and improve waste management in construction [43]

Table 4. *Cont.*

Industry 4.0 Technologies	Triple Bottom Line		
	Social	Economic	Environmental
12. Blockchain	Increased collaboration and transparency among stakeholders. Data security [41]	Cost reduction by eliminating indirect costs and inefficiencies [41]	Improves waste management through the traceability material in the entire project lifecycle [41]
13. Digital Twin	Facilities management, by employing state of the art technologies such as digital twins and digital asset management to improve the environmental issues resulting from the careless consumption of energy related to the greenhouse effect and that can interfere in the societal quality of life [22].	A DT can be used to learn and suggest new scenarios before building a product, manufacturing tools and equipment, because developing a construction process, and planning for developing, avoiding loose time, natural resources and money [17,40].	

6. Final Considerations

The general objective of this work is to offer a current overview of publications that associate the civil construction sector; Industry 4.0 Technologies and sustainability, and identify the challenges and opportunities of the Industry 4.0 Technologies set to contribute to sustainability achievement. This study helps researchers and practitioners, with tables of reference that serve as a guide to advance the study of technologies and to address the current shortcomings of such technologies, while enhancing their sustainability contributions to processes in future building construction. To the best of the authors' knowledge, this study is the first of its kind using Civil Construction, Industry 4.0 Technologies, and Sustainability to propose a unified table to help managers and academics understand these relationships.

In the current scenario, where the civil construction industry continues to generate a large waste of resources such as water, energy and materials, the use of technologies can help improve the performance and competitiveness of the sector, in addition to contributing to achieving sustainable development goals. The central premise behind the use of technologies associated with Industry 4.0 is to generate efficiency and optimize production processes in a continuous and upward manner, that is, the use of resources in a reduced, precise, intelligent, and autonomous way, which generates greater productivity, quality and customization. Thus, from the bibliographic and bibliometric review, it is possible to verify that disruptive technologies support the new industrial paradigm, that can be applied in building, to improve the performance of the construction sector and render it more sustainable and intelligent using modeling systems and virtual simulation of projects, 3D printing, robots, drones, sensors, and the Internet of things (IoT).

The bibliometric review identified state of the art methods relating to Civil Construction; Industry 4.0 Technologies and Sustainability and pointed out that there are still few papers in this field and there remain gaps to be explored, not only by civil engineering, but by professionals and multidisciplinary researchers. Furthermore, it was noted that technologies are still secondary on the research topics, showing that there is space for them to be empirically explored and to become protagonists in the coming years. Another point is the developing countries, including Brazil, which are still adept at manual civil construction and poorly trained and digitalized, allows for growth in performance of the industry 4.0 technologies and Sustainability and solidification of the tools and practices that transform the current context. These findings also reflect in academic contributions, directing new lines of research in possible research gaps addressed in this article.

Through a bibliographic review of the literature, the research was able to point out what Industry 4.0 Technologies, challenges, and opportunities Civil Construction has experienced. From the review, it was possible to identify and present in a structured way the applicability of the industry 4.0 technologies within the scope of civil construction, by elaborating a comparison between the adoption of technological tools and the previous scenario of the sector.

That is why investing in technological intelligence means directing the strategy towards flexibility, which can significantly favor the civil construction sector, especially in issues of cost reduction, improvements, and alternatives to the productive process in search of transformation in the way of acting, thinking and doing. Therefore, it is concluded that Industry 4.0 Technologies can contribute to civil construction through innovative, sustainable, and technological solutions focused on the flow of work, which are able to provide growth to civil construction through the balance of costs/benefits in the management of projects and works. For future studies, the development of a systematic review of the literature is recommended, which can identify other opportunities and challenges, besides the practical and applicability of the use of new technologies aligned with the environmental, social, and economic pillars in the scope of civil construction.

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