Review

A Systematic Review of Construction 4.0 in the Context of the BIM 4.0 Premise

Hana Begić * and Mario Galić

Faculty of Civil Engineering and Architecture Osijek, Josip Juraj Strossmayer University of Osijek, Street Vladimir Prelog 3, 31000 Osijek, Croatia; mgalic@gfos.hr
* Correspondence: hbegic@gfos.hr; Tel.: +385-31-544-687

Abstract: This paper presents a systematic review of Construction 4.0 in the context of the building information modeling (BIM) 4.0 premise. It comprises a review of the industry in the pre-fourth industrial revolution (4IR) age, the current and anticipated development of the 4IR, Construction 4.0's origin and applications, and the synergy of its main drivers, i.e., the synergy of BIM with the internet of things (IoT) and big data (BD). The main aim of the paper is to determine the Construction 4.0 drivers and to what extent are they initialized by the 4IR, their development and their synergy with BIM, and the direction of BIM's implementation in the construction phase. It was found that the main drivers of Construction 4.0, which originated from the 4IR, are BIM, IoT, and BD, but with specific implementations. The results of the analysis of BIM with IoT and/or BD revealed that the integrative approaches combining the aforementioned drivers show signs of project enhancement by providing significant benefits, such as improved real-time monitoring, data exchange and analysis, construction planning, and modeling. Furthermore, it was revealed that the main drivers are mostly applied in the project's preconstruction phase, which is continuously developing and becoming more automated. The state-of-the-art review presented in this paper suggests that BIM is in transition, adopting Construction 4.0 to become BIM 4.0.

Keywords: BIM; Construction 4.0; Industry 4.0; IoT; Big Data

1. Introduction

The fourth industrial revolution (4IR), also colloquially referred to as Industry 4.0, is expected to bring growth, enhancement, and accelerated development to most industries in the near future. In comparison to the previous technological revolutions, the 4IR could be the first revolution simultaneously active in most parts of the world, due to globalization trends. Industries that have already stepped in and adopted the 4IR report that 4IR changes are mostly stimulated by the emergence of new technologies, i.e., drivers, such as digital twin construction (DTC), building information modeling (BIM), internet of things (IoT), Big Data (BD), and additive manufacturing (AM)/3D printing. These technologies have, to a certain extent, already changed most industries, but industries are still not seriously adopting the full potential of the 4IR. An example of such partial implementation of the aforementioned technologies is the construction industry, which in light of the 4IR is often referred to as Construction 4.0. The introduction of the Construction 4.0 concept and new technologies is anticipated to be a major challenge for a commonly sluggish industry. Among numerous recent reports and strategic studies regarding Construction 4.0, a report published in 2016 by the Roland Berger consultant company [1] stated that Construction 4.0 provides a variety of possibilities for stakeholders in the construction industry to boost their productivity in all kinds of ways. However, just 6% of construction companies of construction companies make full use of digital planning tools, while 93% of them agree that digitization will affect every process. Despite the poor adoption rates, a report from 2019 [2], published by the Publications Office of the European Union, underlines the potential of digital transformation in the architecture, engineering, and construction (AEC) sector as

extremely significant since it can bring about improved efficiency, competitiveness, and better resource utilization for the construction industry. Due to the size of the construction industry, even small improvements would result in significant benefits for society since construction is a determinant of where and how most people live and work [3].

The construction industry is considered to be in a continuous reengineering phase, with recent innovations showing the immense contributions of significant aspects such as safety, sustainability, project performance, lean production, site monitoring, design, construction automation, etc. Construction 4.0 has increasingly attracted the interest of academics and professionals in the last few years, judging by the growing number of papers published addressing the topic. Perhaps the most systematic and comprehensive literature review of the 4IR's impact on the construction industry was published in 2016, in which the authors still referred to Construction 4.0 using the German term "Bauen 4.0" [4]. The authors presented the technologies associated with the concept of the 4IR in the context of the construction industry and provided a look at the state of the art of those technologies. Among numerous important and insightful conclusions, the authors underlined that Construction 4.0 comprises many interdisciplinary technologies that are at different levels of maturity: some are widely applied, and some are still being developed. A survey regarding the maturity of technologies was conducted in [5], where the aim was to determine stakeholders' opinions on given questions. The results were surprising as they showed the same levels of maturity of technologies. The authors believe that the results can be highly influenced by the type of stakeholder, i.e., different technologies will reveal different maturity levels depending on the role of the stakeholder in construction projects. In the context of the implementation of such diverse technologies, the integrated design and delivery solutions (IDDS) framework can be of use, while the emergence of new technologies such as off-site manufacturing and construction design and build automation will ensure the optimal development of IDDS [6]. Klinc and Turk [7] explained the Industry 4.0 concept in terms of the historical evolution from Industry 1.0 to Industry 3.0. The paper highlights the fact that, before Industry 4.0, a human mediator between the real and the digital world was necessary. Additionally, they stated that cyberphysical systems are the key technology of Industry 4.0. Another study provided a survey of DTC systems, identifying the business platforms, implementation barriers, and challenges for future development [8]. The authors pointed that, even though it may seem like it, DTC is not just a logical progression from or extension of BIM. Rather, DTC frames a comprehensive mode of construction by prioritizing the closure of control loops upon reliable, accurate, thorough, and timely information.

In another interesting and informative literature review [9], the authors focused on Construction 4.0, providing a map of the research themes and clusters over 10 years of scientific publications. The authors highlighted that BIM, as a keyword, was most mentioned, and showed that augmented reality (AR) and virtual reality (VR) are relevant to the Construction 4.0 concept as well. Although the numerous benefits of BIM are well recognized, BIM has still not reached its full potential in the construction industry, especially in the construction phase of projects. While BIM is, arguably, highly applied in the construction design phase, it continuously lacks integration in the realization, i.e., on-site implementation in the construction phase.

Our main motivation, based on the further study topics discussed by Osterreicher and Tetueberg [4] and Boton et al. [9], was to determine whether the main drivers of Construction 4.0 are what it takes to reach BIM's potential in the construction phase. Although the scope of BIM benefits is well recognized, BIM has still not reached its full potential, especially in the construction phase of projects. There are recently published papers confirming sluggish BIM adoption and the main barriers to its implementation worldwide [10–15]. Among the numerous barriers reported in the aforementioned papers, most lie in the required knowledge, effort, initial costs, traditionalism, and inadequate organizational support for BIM's full implementation in the entire project life cycle. One recent study [16] underlined the main contractual issues associated with BIM and connected

the current treatment of BIM with uncertainties concerning the existing legal paradigm as a barrier to the full use of BIM. A well-received contribution towards helping the industry worldwide can be directly connected to the development of the ISO 19650 standard. The aforementioned standard ISO 19650 consists of six parts [17–22] so far. It is an international standard for managing information over the whole life cycle of a built asset using BIM. It is important to underline parts 3 [19] (i.e., ISO 19650-3 Organisation of information about construction works—Information management using building information modelling—Part 3: Operational phase of assets) and 5 [21] (i.e., ISO 19650-5 Organisation of information about construction works—Information management using building information modelling—Part 5: Specification for security-minded building information modelling, digital built environments and smart asset management), which aim to aid BIM's adoption in the construction phase. For this research, part 5 of the ISO 19650 standard, stating that "the security-minded approach can be applied throughout the lifecycle of an initiative, project, asset, product or service, whether planned or existing, where sensitive information is obtained, created, processed and/or stored," has the most importance, especially in terms of security-minded building information modeling, digital built environments, and smart asset management.

We hypothesize that BIM in Construction 4.0 will metamorphose into an active internet data exchange environment, i.e., BIM 4.0. The main research questions that arose are structured as follows:

RQ1—By which drivers, and to what extent, is Construction 4.0 initialized by the 4IR?

RQ2—What are the relationships among the main drivers of Construction 4.0?

RQ3—What are the key directions of BIM development regarding the other main drivers of Construction 4.0?

RQ4—Is BIM 4.0 directed towards the construction phase, and will this enhance its overall adoption by the construction industry?

The remainder of this paper is organized as follows. In Section 2, the applied research methods are thoroughly described. Section 3 presents the literature review, focused on the 4IR. Section 4 includes the Construction 4.0 paradigm and a detailed analysis of each of its detected drivers. Meanwhile, Section 5 analyzes the current state of the art in the area of BIM integrated with IoT and BD. In Section 6, there is a discussion and in Section 7 conclusions are drawn.

2. Research Methods

This paper presents a systematic literature review, with references filtered and extracted from recently published relevant scientific papers, reports, and conference papers indexed in Web of Science and Scopus. Since the topic is developing worldwide, there have been numerous studies published in the past decade. The research was initialized by determining the main keywords (i.e., third industrial revolution, fourth industrial revolution, industry 4.0, construction 4.0, cyberphysical systems, CPS, digital twins, BIM, BIM 4.0, internet of things, IoT, Big Data, additive manufacturing, and 3D printing), which were used in various combinations for each segment of the paper. In Figure 1, the scope and gradual importance of research objectives are presented. Since the topics, i.e., the foci of the research, overlap and can hardly be thematically or periodically discretely separated, their overlaps are presented as fuzzy, as shown in Figure 1.

Due to the fact that the topics of the research move from a wide scope to a single research objective, the main challenge was filtering the relevant literature. In our first literature search, the keywords highlighted in the systematic literature review by Oesterreich and Teuteberg [4] were applied, and we went through several rounds of narrowing, aiming at simultaneous appearances of both BIM and BD, as well as BIM and IoT. The vast majority of references date from 2010–2020, with a few exceptions in the first chapter regarding previous industrial revolutions.

The literature review presented in this research resulted in a total of 172 referenced sources. A standard software tool for constructing and visualizing bibliometric networks, i.e., VOS viewer software, was used to present the keywords referenced in the paper [23].
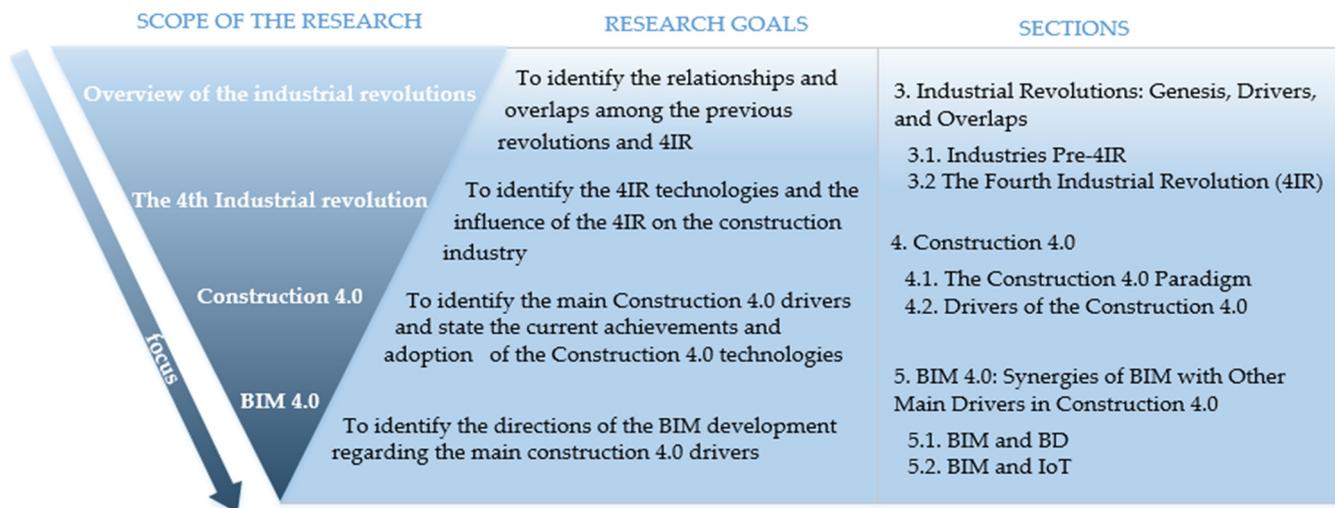

Figure 1. The scope of the research, research goals, and sections.

3. Industrial Revolutions: Genesis, Drivers, and Overlaps

3.1. Industries Pre-4IR

History has shown that industrial revolutions tend to have a slow starting pace, but with time, have a galloping impact on shaping common production technologies, everyday lifestyles, etc. [24]. In general, the term industrial revolution can be defined as a widespread dramatic change in the methods of producing goods and services [25]. Like the previous, i.e., first and second industrial revolutions, the third industrial revolution (3IR) was also driven by technological advances regarding manufacturing, distribution, and energy factors [24]. In the first industrial revolution, it was the printing press, in the second industrial revolution it was radio and television, and in the 3IR, it is/was the combined power of computing, telecommunications, and news broadcasting [26]. It is believed that society will emerge from the 3IR as a dynamic "global village" because technology companies, content providers, and information professionals will empower people to browse, retrieve, share, and use data for personal and professional uses. While the 3IR indeed fulfilled most of its potentials in the majority of the developed countries, in developing economies it still has not [25]. Digital tools and equipment are still becoming widely used for either designing or manufacturing products enhancing the sharing of designs and easier collaboration among stakeholders. Therefore, the manufacturing resources pool is significantly larger in scale than what any single maker could achieve [27]. On the other hand, it is believed that direct digital manufacturing is not merely a stimulus of the 3IR, but one of its effects. The main challenge of the 3IR was found to be the traditionalism of most industries, manifested in the sluggish upgrade of established enterprises in accepting and implementing reengineering [28]. When it comes to 3IR technologies, among others, six major high-technology agents are underlined in the literature, i.e., microprocessor, computer-aided design and manufacturing (CAD/CAM), fiber optics, biogenetics, lasers, and holography [28]. There is a special emphasis on the development of microelectronics technology at this historical juncture [29]. The main reason for its importance is an immense impact on the affordability of computing power. Due to the simultaneous reduction in the cost of computers and the massive increase in their power, the microprocessor made computers accessible to a large number of people who could not have afforded or operated their predecessors [30]. An additional challenge is the interaction between technological changes and the international division of labor [29]. The 3IR began to affect labor in industrialized countries by the

late 1970s because, in developed countries, increased income and living standards made customers more sophisticated and demanding. At the same time, the market for lasting consumer goods was saturated and their demand subsided. As for the negative side effects, unemployment arose during the 3IR and is mostly associated with difficulties in the process of transferring the labor force from industry to services [31]. Additionally, the economic migration of many workers to more developed countries has caused shortages in the workforce in less developed countries, which will continue to persist as a problem in the 4IR [32]. It is anticipated that some of the problems and challenges that the 3IR faced will be resolved in the 4IR, but new ones may emerge.

3.2. The Fourth Industrial Revolution (4IR)

Even though some benefits of the 3IR have not yet reached much of the world's population, in developed countries the 4IR has already taken its place [33]. The 4IR, also referred to as "Industry 4.0," made its first appearance at the Hannover Fair in 2011 [34]. Schwab [33] characterized the 4IR as "a fusion of technologies that are blurring the lines between the physical, digital, and biological spheres." Unlike the previous Industrial Revolutions, the 4IR is progressing at an exponential pace, not sluggishly nor in a linear manner. It is expected that, in the future, technological innovation will reinforce the supply side and bring about gains in efficiency and productivity in the long run. Additionally, production process automation aims to reduce the scale problem of labor force deficiency reported in the 3IR. It is believed that it is necessary to implement new technologies for automation to achieve complete digitization and intelligence of existing industrial processes [35]. Therefore, the future of manufacturing may see industrial production systems become more intelligent by using digital systems to create more knowledge-based productions, which will greatly improve their efficiency and competitiveness.

As described above, the 4IR is considered to be mainly dependent on building a CPS to create a digital and intelligent factory, to navigate manufacturing towards becoming more digital, information-led, customized, and sustainable [36]. The 4IR integrates IT systems with physical systems to get a CPS that brings the real world into VR [37]. Those systems represent the integration of an information system (IT) with mechanical and electronic components that are connected to online networks and allow for communication between machines in a way that is similar to social networks [38]. The cyberphysical integration is also enabled by the digital twin (DT) concept, which can be considered a necessary path to realize CPS [39]. Ultimately, CPSs and DTs enable the integration of production, sustainability, and customer satisfaction while forming the basis of intelligent network systems and processes [40]. Besides CPS and DT, 4IR also uses IoT to connect production technologies with smart production processes to make manufacturing smart [41,42]. The basic idea of IoT is to make "things" around us communicate with each other to achieve mutual goals, with its main feature being the integration of various identification and tracking technologies, i.e., wired and wireless sensors and actuator networks, enhanced communication protocols, and distributed intelligence for smart objects [43]. The implementation of the IoT concept will be enhanced by the fifth-generation mobile network (5G), which is the term used to describe the next generation of wireless networks. The features of the 5G network will provide the user with several performance enhancements regarding network capacity increase, shorter latency, more mobility, and increased network reliability and security, which will, in turn, result in an all-connected environment called the IoT [44]. The final puzzle is the structure or environment that can handle the managed information by CPS and IoT, and that is BD and cloud computing [45]. With that being said, it is clear that one of the most important technologies, besides IoT, adopted in the 4IR is BD, which is related to the collection, processing, and analysis of a large amount of structured and unstructured data with intelligent algorithms [37]. The term BD is derived from the fact that the datasets are so large that typical database systems are not able to store and analyze them; also, the data are no longer traditionally structured, but originate from many new sources including e-mail, social media, and Internet-accessible sensors [46]. Using BD to

replace processes that are done manually may make certain jobs outdated, but may also create new categories of jobs and opportunities that currently do not exist in the market [33]. One of the definitions of BD provided in [47], and also the most widespread one, is the "4V" theory, stating that BD comprises a variety of resources and contains a great volume of data; BD streams in at a high rate and must be handled timely, which implies velocity; BD comes in a variety of formats; BD has to be cleaned to ensure the validity. BD analysis may require a considerable commitment of hardware using the old hardware storage method, but the emergence of cloud computing promises to make it small, by reducing computational costs while increasing the elasticity and reliability of systems [48]. Another important feature of the 4IR is AM or 3D printing, which represents the capability of producing three-dimensional objects from virtual models [45]. According to [49], the advantages of AM are the possibility of designing and developing products. Additionally, companies are using AM to capitalize on its benefits like complexity for free manufacturing, while in traditional manufacturing a direct connection between complexity and manufacturing costs exists. The aforementioned technologies are becoming increasingly implemented in many industries, including in the construction industry, where the whole concept has merited a new term, Construction 4.0.

4. Construction 4.0

4.1. The Construction 4.0 Paradigm

It is a common belief that the first mention of Construction 4.0 dates back to 2016, and was primarily based on construction companies' awareness of the importance of digitization in the construction industry [1,50]. Thus, it can be said that Construction 4.0 is the convergence of industrial production, CPSs, and digital technologies with the ultimate goal of creating a digital construction site [34]. As such, it is anticipated that Construction 4.0 will fundamentally influence organizational and project structures, since the framework of Construction 4.0 enables planning, designing, and delivering built assets more effectively and efficiently, with the focus being on the physical-to-digital transformation and then digital-to-physical [51,52]. Construction 4.0 can be defined as a paradigm that comprises CPSs and the internet of things, data, and services, with the main aim of connecting the digital layer, which consists of BIM and the common data environment (CDE), with the physical layer, which consists of the asset and its lifecycle. Besides CPS, the Construction 4.0 framework also uses digital ecosystems and links them with CPS, which is used as a core driver [53], where digital ecosystems represent "an interdependent group of enterprises, people, and/or things that share standardized digital platforms for a mutually beneficial purpose, such as commercial gain, innovation or common interest." The conceptual model of a digital ecosystem consists of a business network of third-party developers, boundary objects, and a core digital platform [34]. The ultimate goal is to create an interconnected environment that integrates organizations, processes, and information with the purpose of efficiently designing, constructing, and operating assets [54]. According to a report of the Digital Supply Chains in the Built Environment Work Group (DSCiBE) [55], the introduction of BIM can be considered the first step towards a collaborative digital communication and has also pushed the construction industry to look at how it can deliver value through data. The main aim of the report by the DSCiBE task group was the standardization and interoperability of product data as well as digital product identification. As expected, the drivers of Construction 4.0 have their benefits and challenges; the main ones are presented in Table 1.

Table 1. Construction 4.0: main benefits vs. main challenges.

Benefits [4,51,56,57]	Challenges [4,58–62]
adoption of the lifecycle building approach, reduction of waste and efficiency improvement, horizontal, vertical, and longitudinal integration, improving sustainability, cost and time reduction, improved safety performance, enhanced quality of buildings, improvement of the poor image of the construction industry	high initial investments, lack of skilled workforce and the need for enhanced work skills, deficiency of globally agreed standards for the construction industry, data security, i.e., cybersecurity lack of knowledge about Construction 4.0 resistance of the construction industry to change

Identification of the Construction 4.0 drivers, as the initial step in its development, has been a relevant research topic in the last five years. Various authors have identified various drivers, i.e., various technologies that have enabled the emergence of the Construction 4.0 concept. In 2016, popular media such as newspaper articles, magazine articles, blogs, and websites were analyzed to determine which technologies are considered a part of the 4IR. It was found that the central technologies are BIM, Cloud Computing, and IoT. Moreover, it was concluded that all of the 4IR technologies are at different levels of maturity [4]. In 2019, research presented in [63] determined that there is an active collaboration between BIM and 4IR technologies. Additionally, it was found that there is a lack of understanding of the 4IR concept in the construction industry [63]. In 2020, four technologies were determined to be essential to the understanding of Construction 4.0: 3D printing, BD, VR, and IoT. The research was conducted using a bibliometric analysis and by analyzing the keyword occurrence [50]. In the same year, Maskuriy et al. [64] researched the application of 4IR technologies in construction and found that most integrated technologies have focused on the preconstruction phase. Furthermore, in the literature review in [65], it was noted that Germany leads the field of Construction 4.0, and is followed by China, the United States, etc. Moreover, a UK-based multinational construction design consultancy firm was analyzed, and the results showed that there are many barriers to implementing Construction 4.0, such as residual managerial practices. As some of the main enablers for the implementation of the Construction 4.0 concept, the following technologies were identified: IoT, Cloud computing, BD, Artificial intelligence (AI) and robotics, and cybersecurity [65]. Table 2 presents the summarized chronological findings and applied methodologies regarding Construction 4.0 drivers in the last five years.

Table 2. Chronological findings and applied methodologies of Construction 4.0 drivers.

Year, Reference	Methodology	Main Findings—Drivers, Aims and Challenges
2016, [4]	Systematic literature review; Method and data triangulation	Central 4IR technologies are BIM, Cloud Computing, and IoT; 4IR technologies are at different levels of maturity
2019, [63]	Bibliometric mapping study method; scoping review technique	There is a lack of a complete understanding of the 4IR concept in the construction industry; there is an active collaboration between BIM and 4IR technologies
2020, [50]	Bibliometric analysis	4IR technologies—3D printing, BD, VR, and IoT are essential to understand the Construction 4.0 concept; the USA, UK, and China are leaders in publications regarding Construction 4.0; the number of Construction 4.0 publications is growing exponentially
2020, [64]	Classification of existing literature	Most research regarding 4IR in the construction industry is focused on the preconstruction stage
2020, [65]	Synthesis of extant literature; empirical case study	Germany leads in the field of Construction 4.0, followed by China and the United States; residual managerial practices are a barrier to implementing Construction 4.0; main enablers: IoT, Cloud computing, BD, AI and robotics, and cybersecurity

It can be noted that the aforementioned challenges of Construction 4.0 have also been reported by the authors presented in Table 2. Additionally, the most prevalent drivers of Construction 4.0 are considered to be BIM, IoT, and BD, which are mentioned by most of the authors.

4.2. Drivers of the Construction 4.0

4.2.1. Cyberphysical Systems (CPS) and Digital Twins (DT)

The stimulus for applying CPS in the construction industry is their integration of physical systems and their virtual representations, i.e., their DTs, to create an integrated analytical system, where a DT is the real-time digital representation of a building or infrastructure [66]. Such a system should be able to adapt to changes at construction sites and connect the virtual world with the physical world by using sensors or data acquisition technologies and actuators [67,68]. The changes should update the state in the form of measurements, data, and pictures, which are then updated in the DT and allow for continuous monitoring of a 4D BIM model [66]. According to [34], CPS consists of the physical part, which is usually a device, a machine, or building, and a cyber part, which is usually data, a software system, or a communication network. Furthermore, CPSs are systems of interconnected physical and digital twins, where the digital twins are the virtual assets or simulations of the physical object in real time. Additionally, digital and physical twins are reciprocally connected by sensors and actuators. By enabling a tight connection between computational models and associated physical entities, the integration of CPS and DT offers a way for construction project teams to bridge the gap between virtual models and physical construction and can therefore be considered the "heart" of Construction 4.0 [58]. Many innovative technologies, such as prefabrication, automation, 3D printing, VR, AR, unmanned aerial vehicles (UAV), sensor networks, and robotics for repetitive or unsafe procedures, are enabled by bidirectional communication between construction components and their digital representations [34,58]. Therefore, the built environment is a rich area for the application of the CPS and DT framework since smart buildings, cities, and infrastructure are all examples of what may be called cyberphysical environments, where the built environment becomes increasingly intelligent and digitally connected [69]. Ultimately, CPS can be considered as the key to achieving more efficient, safer, and more environmentally friendly construction projects, which are also the goals of Construction 4.0 [34]. As mentioned earlier, CPS consists of two principal elements, i.e., the "physical to cyber" bridge and the "cyber to physical" bridge [70,71]. In terms of construction, the physical to cyber bridge represents construction components and processes that are tracked using sensors and other tracking systems [58]. In addition, the progress and changes in the construction process are monitored and coordinated with their associated cyber representations for further action. The cyber to physical bridge covers the actuation dimension and dictates how the information from the sensors is used to manage the system, which means that actuators in this sense involve transmitting appropriate information to enable prompt decision making. Improved safety has the potential to be the key benefit of implementing CPS and DT in the construction industry since it is predicted that project managers and safety specialists will have access to locations of employees and heavy equipment at all times [72,73]. Additionally, sensors have made data exchange among workers easier and provided opportunities to monitor their health to increase safety [74]. Moreover, structure monitoring sensors can detect malfunctioning structural components to ensure site safety.

In [58], the application of CPS for various purposes in the construction industry was analyzed, such as for construction component tracking, temporary structure monitoring, and mobile crane safety. Furthermore, a cyber model named Petri Net [75] was adopted as a model for a construction process and two application scenarios of automatic assembly and traditional structural masonry were simulated. In [76], a citizen service center was presented for the verification of the technical feasibility and implementation effect of a CPS framework, in which the real-time construction model acts as the digital twin of the

building under construction. It was concluded that, benefitting from real-time monitoring, simulations, and the decision support mechanism of the proposed CPS, future construction plans will no longer be fixed and predefined, but it will be possible to make and adjust schedules according to the actual situation in the construction process.

4.2.2. Building Information Modeling (BIM)

The subject of BIM currently represents a central topic for the improvement of the construction industry, and simultaneously a core technology for supporting the idea of the 4IR in the construction industry [4]. Since BIM is increasingly being adopted and utilized in the architecture, engineering, and construction (AEC) domain [77], it can act as a catalyst for deeper adoption of digitization, which is also due to the quick and good acceptance it has received [78]. As the center of the digitization of the construction industry, together with the 4IR concept, BIM can close the digital gap that still exists and have a positive impact on future building processes [79]. By incorporating various properties, BIM can offer a high-accuracy representation of a project at the level of components [76], and an integrated three-dimensional model can be adopted to completely express the definition information of buildings [80]. An important feature is the bidirectional coordination between the physical and virtual domains. That coordination leads to a digital replica of the building, which improves the control and optimization of the construction process while also generating valuable data for the building's operation/maintenance, as well as for the design and planning phase of future construction [63]. The mentioned virtual replica of the building can be compared to a similar concept in the manufacturing industry called the digital twin [81]. Various subsets of BIM can be referred to as dimensions, where 3D is the object model, 4D is time, 5D is cost, 6D is operation, 7D is sustainability, and 8D is safety [59].

Among others, an interesting study that represents a notable example of the importance of BIM by pointing out that BIM can help users share project information during the entire construction lifecycle was presented in [82]. The building's information is available to everyone included in the construction project, from the design team to the construction team and the owner of the building. Additionally, all mentioned project members have the possibility of adding or changing information during their period of using the BIM model, which is done by the integration of BIM into cloud computing. Thus, the project stakeholders can collaborate in real time from different locations to enhance decision-making and ensure project deliverability [83]. BIM is also useful in terms of reducing the data size, because the volume of data collected from construction projects is massive due to the complexity of their designs and construction activities [84]. However, with the support of BIM, the volume of data that is related to the design of a three-story building can easily reach 50 GB [85], which burdens the data-interoperability and data-transfer processes.

Alongside all the benefits stated, it is important to mention the main challenge that BIM faces, which is related to the full implementation of this technology in all phases of the design, construction, and operation of buildings [86]. Moreover, the biggest constraints on the mainstream application of BIM refer to the lack of scalability, interoperability, and support for remote collaboration [87,88]. Several studies have been carried out on the use of BIM in the construction industry, e.g., on cloud-BIM [83] and also linking BIM to construction lifecycle phases [89]. Furthermore, a paper presented the linkage between sensor and BIM by using IFC (industry foundation classes) [90]. Additionally, research was conducted on the development of construction industrialization based on BIM methodology, and a navigation framework was proposed for the inclusion of BIM and factory equipment to simulate a digital twin factory [91]. Another interesting paper is [92], wherein the potential of BIM and the 4IR to change the future of the construction environment was discussed.

In the context of recent trends of BIM development, it is important to mention integrated building information modeling (iBIM). According to [93], the main aim of iBIM is to integrate BIM with other innovative technologies and managerial approaches during

the project life cycle. To enhance the project performance, BIM can be integrated into three stages of the project: the preconstruction phase, the construction phase, and the facility management phase. The preconstruction phase concerns the integration of BIM with materials tracking and logistics systems to benefit from supply chain management [93]. An example of such integration is presented in [94], in which the potential of BIM to provide contextual information mapping across processes was observed. It was also stated that the integration of design, manufacturing, and construction processes, with transparency of information about material resources across these processes, would bring about significant benefits for all stakeholders within the supply chain. The integration of BIM and GIS was used in the planning and designing phase of the building for activities such as construction site selection, energy design, structural design, performance evaluation, etc. [95]. Another interesting example of integrating BIM and GIS in the planning phase of construction is a case study that presented a BIM–GIS system for visualizing the supply chain process and the actual status of materials through the supply chain [96]. Furthermore, multiple studies regarding the integration of BIM and RFID for various purposes were conducted [97–100]. In the construction phase, conceptual frameworks have been researched for the integration of BIM and AR [101,102]. It was investigated how BIM can be extended to the site via AR to improve the way information is accessed [103]. Furthermore, BIM can also contribute to quality management by integration with Light Detection and Ranging (LiDAR), with the purpose of better evaluation of on-site conditions and achieving real-time construction quality control [104]. The last phase is the maintenance/operation phase, in which the integration of BIM and LiDAR has also found its application; an example is the automated inspection of the quality of prefabricated houses [105]. This phase reflects the integration of BIM and AR, which is extremely useful in the field of facility management; an example is a BIM2MAR method tested in a facility management pilot study [106]. The versatile possibilities of BIM application in the construction industry could be the foundation for the change that the construction industry needs.

4.2.3. Internet of Things (IoT)

A technology that brings physical objects into a cyber world that is based on devices or technology such as sensors, actuators, RFID, video cameras, and laser scanners is called the IoT [76,107]. According to [108], the IoT is a set of four different layers, i.e., an application layer, a perception layer, a network layer, and a physical layer. The layer that refers to smart cities, smart transport, and intelligent homes is the application layer. The perception layer refers to technologies that communicate with other objects, like sensors and devices. Furthermore, the network layer refers to the network communication and the component of network coverage, while the physical layer refers to the hardware and includes smart appliances and other devices. The use of the IoT in the construction industry has many possibilities and benefits, mostly focused on fast decision making due to the availability of real-time data analytics [109,110]. In addition, IoT technologies and applications could transform the construction, maintenance, and operation phases by maximizing user comfort, security, and energy saving by diverse intelligent solutions [111]. However, it is believed that most current IoT solutions in the construction industry are isolated for specific applications but lack coordination over the entire construction process [76]. Research carried out and presented in [112] determined the dominant challenges to applying IoT in the construction industry. It was found that these challenges are a lack of safety and security, a lack of documented standards, a lack of awareness of the benefits, the improper introduction of IoT, and a lack of robustness in connectivity. These challenges have also been reported in other papers [113–115].

Despite the mentioned challenges, the IoT has been widely accepted in the construction industry. For example, by taking advantage of the IoT, the real-time data collected from a construction site drives BIM models to monitor the construction process [116]. An interesting application of IoT in construction is a prototype that was designed for an IoT-based construction site safety management system [117] that can be operated at a

low cost independently of the size of the construction site. Additionally, a model for construction site safety monitoring [118] was developed that identifies real-time safety problems and also stores data for future training and improvement. The same paper provided a cost comparison that showed that an IoT system can provide around a 70% cost savings in comparison to traditional systems. Another IoT-based system regarding worker safety with real-time alarming, monitoring, and positioning strategies was introduced in [119], and a safety recognition service using an IoT sensor network in [120]. A commonly reported method is the establishment of a mapping structure between the IoT data and BIM data [76]. The IoT can also be used for integrating environmental and localization data in BIM [121]. Additionally, the IoT can be used in conjunction with the "cloud" to achieve real-time data transmission for monitoring systems, as presented in [122,123]. A similar approach based on the BIM platform for the on-site assembly of prefabricated construction was provided [124], which is enabled by the IoT, while an example of IoT utilization for real-time decision making in repetitive construction operations was presented in [125]. The mentioned applications of the IoT in the construction industry show the versatile benefits it can bring to the construction industry. However, as mentioned earlier, the IoT is a multilayer system that requires wider collaboration for reaching its potential. It is important to research its collaboration with other drivers such as BD.

4.2.4. Big Data (BD)

Due to the rapid development of information and communication technologies, the construction industry is entering the BD era. The term BD can be seen as a rebranding of the term data mining, with a focus on larger and more diverse datasets and sources, with data mining being the technology of discovering structures and patterns in large datasets [126]. BD is believed to be induced with the use of technologies such as radio frequency identification (RFID), and sensor networks [84,127]. Consequently, it is becoming possible to easily collect and effectively use the massive volumes of data that are generated by various design and construction activities to enhance the performance of construction projects [128]. The significance of BD is not to manage a massive amount of data, but to extract valuable information from them.

Referring to the construction industry, BD presents data generated from the life cycle of the building or structures, which includes the phases of planning, design, tendering, construction, checking, and operation management [76]. BD analysis is valuable for more efficient project delivery and for all project stakeholders. Privacy and security issues, skill requirements, data access, sharing of information, and storage and processing issues have been recognized as some of the main challenges of BD [129]. A detailed overview of issues in the field of privacy and security of BD was provided in [130]. Agrawal et al. [131] listed the heterogeneity and incompleteness of data, the scale of data, and the timeliness of analyzing data as the main challenges of BD. Methods of analyzing BD include statistical analysis, online analytical processing (OLAP), and data mining [76]. Besides the expected growth of data from construction business operations, automation of construction processes, safety monitoring/control, resource management, etc. will also lead to significantly more data being generated in the near future [128]. For instance, images from construction activities can be used to identify unsafe behavior of construction workers, with the purpose of reducing the occurrence of safety accidents [132]. Furthermore, multiple studies have reported that BD has the potential to generate immense value for construction projects while effectively improving project performance [84,127]. In addition, based on machine learning, BD can be utilized to accurately predict the performance of construction projects and detect possible uncertainties in project outcomes while still at the early design stage [133]. By mining cost-related data collected from previous projects, strategies can be implemented to control future project costs [84]. An interesting field worth mentioning is the utilization of BD to support smart cities [134]. Lu et al. [135] presented the possibility of using BD in construction waste management and even used BD analytics to identify illegal construction waste dumping [136]. Moreover, it was concluded that an accurate analysis of BD makes it

possible to discover new phenomena characteristic of the project, which can help reduce risks in project management [137]. Considering the above, BD can be seen as a crucial component of Construction 4.0 due to the increasing amount of data generated by new IoT devices and BIM-related information.

4.2.5. Additive Manufacturing (AM)/3D Printing

During the past decade, the field of AM, and in particular 3D printing, has gained immense attention in terms of industry usage, technological development, and consumer popularity [138]. It is believed that the first patent for 3D printing dates back to 1984 [139], and experimental applications of AM in the construction industry started appearing in the late 1990s [140]. The paradigm of AM is that a structure can be built by adding an elemental material in a way that can easily be automated [140]. It can also be considered as a process that is based on a three-dimensional digital model that uses automatic technology to create physical objects layer-by-layer without human intervention [141]. If we compare additive with traditional manufacturing, AM offers new possibilities for the design and development of products [49]. It is believed that AM can be a vital component of the 4IR or smart manufacturing due to its high capability as a nontraditional manufacturing approach for mass customization [142]. When talking about construction, AM has the potential to help the construction industry to transition into a technically advanced sector [143], which is proven by the fact that the implementation of AM in the construction industry has resulted in various technical breakthroughs and improvements in construction output efficiency [34].

Perhaps the first case of AM in the construction industry was reported in 1995, when the first construction-scale AM method called "Contour Crafting" (CC) was patented at the University of Southern California [144]. There are various terms encountered in the literature that refer to AM in the construction industry, so printing objects roughly above one cubic meter in volume is referred to as "large-scale AM," or popularly as "large-scale 3D printing" [145]. The International Organization for Standardization and the American Society for Testing and Materials classified AM into seven categories: vat photopolymerization, material jetting, binder jetting, material extrusion, powder bed fusion, sheet lamination, and directed energy deposition [146,147]. However, to date, the processes that are being used for applications in the construction industry include extrusion-based processes and binder jetting [148]. There are various applications of AM in the construction industry and there are even some records claiming different levels of success in printing buildings. For example, two cases of 3D-printed bridges, with one printed from metal and the other from concrete, have been reported [149]. A house in Russia was printed using mobile 3D printing technology, and the building envelope was created in 24 h [150]. In 2015, a five-story apartment building with an area of about 1100 square meters, which is considered the highest 3D-printed structure, was finished [151]. Furthermore, in 2016 the same authors presented the first 3D-printed office in the world [152]. It is suggested that AM could contribute to the construction industry by reducing the exposure of on-site workers to harsh environments and by automating some construction tasks [153]. The main benefits of 3D printing were reported in [149], i.e., new possibilities of design, detailed construction accuracy, reduction of waste, increased safety of workers, possibility of combining different types of materials, and the possibility of printing mechanically connected parts. Additionally, the use of AM in construction could lower the demand for a skilled workforce. On the other hand, imperfections, costs, production duration, limitations of materials, and spatial limitations have been mentioned as the major challenges of AM [142]. The main weaknesses of 3D printing are recognized as possible errors in digital model creation, inappropriate materials, lower production speed, the high price of new technology compared to traditional processes, different mechanical properties caused by material layering, poor surface quality, and the lack of technical standards and regulations [149].

5. BIM 4.0: Synergies of BIM with Other Main Drivers in Construction 4.0

5.1. BIM and BD

The essence of BIM can be found in data and information, which explains why BD can be used in the BIM process since BIM will continue to develop. However, a single BIM model is not sufficient to exploit the benefits of BD, and it can take a whole repository of BIM models to be mined for information extracting [154]. Therefore, an emerging trend is the striving for BIM to transfer from personal computers to cloud BIM with the purpose of the project's stakeholders being able to work on BIM from anywhere using their portable devices and access any information necessary for the project [155]. This would enable the data from the cloud sourcing to stay in the BIM and provide support for decision making on a project. Still, the wide usage of BIM is characteristic of the preconstruction stages, while it progressively decreases towards the later stages of a project [156]. Due to the considerable amount of data contained in the BIM model and projects, it can be predicted that BIM could become the center for BD [157,158]. With the accumulation of such amounts of data, the adoption of BIM may be crucial for the creation of a resource for BD analysis [155]. Furthermore, the BD that is contained in BIM can be considered a gold mine for companies to exploit for better decision making and predicting [155]. However, the increasing size and scope of the BIM models are starting to restrict the possibilities of traditional systems being used for storing and processing BIM data [84]. Thus, many cases are going to require customized means of storing and processing BIM. Therefore, BIM-specialized BD storage and processing platforms can be expected [84]. A cloud-based BIM has the potential for providing real-time quantity information due to the advancements of BIM and BD and could stimulate the usage of BIM in the construction phase [155]. Thus far, BIM has been considered to contain only information regarding construction, but the emergence of linked building data is slowly changing this widely accepted attitude [159]. Interesting examples can be found in the connection of BIM with Linked Open Data datasets that contain information on weather, flooding, population density, road congestions, etc. [159,160]. Furthermore, the possibility of using BD in BIM for construction waste minimization was analyzed [161]. A study was conducted in which the need for integrating BIM and BD for maintenance of the lifecycle data and maintenance of the assets and conditions of a highway was stated [162]. Another example was presented in [163], where integration provided cloud computing for the project's members for the facility management. Additionally, a cloud-based system framework was proposed for viewing, analyzing, and storing massive BIM models, and the system was based on Bigtable and MapReduce [164]. The problem with adopting prefabricated construction, i.e., insufficient information for reviewing prefabrication alternatives and choosing suppliers, was recognized in [165], and a system for integrating BIM and BD with the purpose of connecting clients with information about the time and cost of prefabricated elements production was presented. These kinds of integrations of BIM and BD are leading to Big BIM Data, which justifies the emergence of BD as a specialized area of BIM [84]. Additionally, the integration could result in benefits such as better decision making, more efficient modeling and design, failure detection, damage detection, and safety and activity monitoring [84]. Considering the abovementioned applications, the integration of BD with BIM clearly has the potential to reduce the size of data, which can then be used for various purposes in BIM such as weather forecasting, facility management, supplier and alternative selection, and the overall improvement of a construction project.

5.2. BIM and IoT

Until recently, the project's stakeholders would enter information regarding their part of the project, i.e., input parameters, in data libraries. This is considered a passive BIM approach [166]. An active BIM approach aims at dynamic data exchange among BIM and sources of input parameters. Active BIM is considered the approach where the integration of BIM and IoT can find application, and a few examples of such integration are presented in the following.

A software architecture for the integration of heterogeneous IoT devices with BIM and GIS was presented. The information from the IoT devices provided the BIM model with actual data and also evaluated the validity of it [167]. A similar example of the integration of environmental and localization data in a cloud-based BIM platform using IoT and BIM was introduced and the platform was validated in two case studies for construction and facility management and operation [121]. Furthermore, an approach using BIM and IoT for construction site management was presented whereby the principle was based on the connection of BIM through a VPL (visual programming language) to a database where information received from the sensors at the site was stored [168]. Such integration could increase productivity and decrease construction duration and costs due to real-time on-site information monitoring. Integration of BIM and the IoT platform for projects involving prefabricated houses was developed. Stakeholders' demands were collected and analyzed and then RFID technology was used for collecting real-time data from the site [124]. Additionally, a system for visual utility tunnel environmental monitoring based on the integration of BIM and IoT was developed [169]. With smart houses becoming the standard, a case study was presented in [170], where the geometry of a building was fundamental in which IoT devices were integrated. It was found that additional software for Autodesk Revit is necessary to be able to visualize and analyze data from the sensors on the 3D model. A paper reviewed all sorts of domains regarding the integration of BIM and IoT, such as construction operation and monitoring, health and safety management, construction logistics and management, facility management, and the methods for its realization [171]. An interesting study was conducted [172] in which the authors integrated BIM and IoT using sensor data and compared it to the model for indoor environment monitoring and comfort analysis. In addition, the system user could judge whether the thermal comfort level had met the standards and the data could guide future equipment choice. Due to the fact that IoT is an emerging technology, and the number of its devices is rapidly growing, the mentioned applications have taken place in the past four years, and it is anticipated that they will continue to develop at an exponential pace.

6. Discussion

The literature review presented in this research resulted in a total of 172 referenced sources. A standard software tool for constructing and visualizing bibliometric networks, i.e., VOS viewer software, was used to present the keywords referenced in [23]. Figure 2 presents a network map of keywords that appeared in the references based on text data. The keywords were extracted from the abstract and title field of the references applying the full counting method, and with a determined minimum of three occurrences. There were 211 such terms, but the default choice was set to 60% of the most relevant terms, so there were 127 terms analyzed. A further output of the reference network presentation is shown in Figure 3, i.e., mostly referenced journals. This graphical representation supports the relevance of referenced findings, highlighting the journals indexed in Web of Science with a high quantitative bibliometric.

The 4IR differs from the previous industrial revolutions mostly by presenting integrative polyvalent technologies. Therefore, the 4IR already has and will have a much wider scope than the previous industrial revolutions. Even though the 4IR has already taken place in many countries, in developing countries the 3IR has not still fulfilled its potential and it is uncertain when or if the 4IR will appear in those countries. The development of 4IR technologies has stimulated many changes in all sorts of industries, including the construction industry.

Throughout this extensive research review, it is clear that the 4IR is being accepted in the construction industry since the number of papers and the number of presented applications of 4IR technologies in the construction industry is continuously growing. Consequently, the drivers of the 4IR are found to be the drivers of Construction 4.0, except for BIM, which is dominant for the construction industry itself. Although induced by the 4IR, Construction 4.0 is conceptually more focused. An extensive research on the drivers of

Construction 4.0 was undertaken. The most important are presented in this paper, with their benefits, challenges, and possibilities of application. The main drivers of Construction 4.0 were found to be BIM, BD, and IoT since they are the keywords that appeared most often in the analyzed papers, as confirmed by the visual representation in Figure 4. These technologies have provided the basis for most of the current advances in the construction industry.

Figure 2. Network map of referenced keyword clusters.

Figure 3. Network map of referenced journal clusters.

Figure 4. The main Construction 4.0 drivers.

Using VOS viewer software, a map based on text data was created to give insight into the main Construction 4.0 drivers. Figure 4 is related to Figure 2, presented in the section on research methods, but with an increased number of term occurrences. The keywords were extracted from the abstract and title field with a full counting method, and the minimum number of occurrences of a term was five. There were 211 such terms, but the default choice was set to 60% of the most relevant terms, which resulted in 127 analyzed terms. After determining the main drivers of Construction 4.0, their synergy with BIM was analyzed in order to determine whether it will enable their—but, most importantly, BIM's—full potential in all phases of the construction industry. Despite the potential that Construction 4.0 shows throughout its technologies and application to transform the construction industry, most of these technologies are still mostly represented in the preconstruction phase of the project's lifecycle, in which their use is continually developing. Consequently, this is also the case for BIM, which is used worldwide in the design phase, but still lacks application in the later phases of a project's lifecycle, from which the construction industry and the project's performances could undoubtedly benefit. The reason behind this can be found in the well-known traditionalism and resistance of the construction industry to changes and innovations, which are mainly caused by traditional practices and the lack of a skilled workforce. The ISO 19650, namely parts 3 and 5 (i.e., ISO 19650-3 Organisation of information about construction works—Information management using building information modelling Part 3:—Operational phase of assets; ISO 19650-5 Organisation of information about construction works—Information management using building information modelling—Part 5: Specification for security-minded building information modelling, digital built environments and smart asset management) backs up the development of BIM in terms of intelligent information systems with a clear intention for increasing the automation and digitalization of the construction production.

The integration of CPS and DT offers a way for construction project teams to bridge the gap between virtual models and physical construction, creating a cyberphysical production system. In this context, the built environment becomes a rich area for the application of the CPS and DT framework for smart buildings, cities, and infrastructures, colloquially called

cyberphysical environments, where the built environment becomes increasingly intelligent and digitally connected.

7. Conclusions

This paper presents a literature review of the industry pre-4IR, the 4IR itself, Construction 4.0 technologies, its origin and its applications, and the synergy of the main Construction 4.0 drivers, i.e., the synergy of BIM with IoT and BD.

With the aim of answering RQ1, Section 3.2 introduced an explanation of the 4IR and Section 4.2 gave the main Construction 4.0 technologies. It was found that the Construction 4.0 drivers are indeed the drivers of the 4IR, i.e., they originated from the 4IR, except for BIM, which is characteristic for the construction industry. Most of these technologies did exist for themselves, but it was the concept of the 4IR that pushed them into wider application and gave them more popularity by increasing interest in the whole concept.

To answer RQ2, each of the Construction 4.0 technologies was analyzed in Section 4.2 and a visual representation was made (Figure 4). It can be concluded that BIM, BD, and IoT are the most represented, i.e., the most significant Construction 4.0 drivers. Ultimately, it was concluded that BIM, IoT, and BD are the main drivers of Construction 4.0. This provided a basis for answering RQ3, in which the aim was to determine the directions of BIM development with regard to the main Construction 4.0 drivers and whether Construction 4.0 is what will push BIM into wider application. The motivation for this question was found in the fact that BIM is mostly applied in the design phase of construction but lacks application in the later phases of a construction project.

In order to answer RQ3, Section 5 was dedicated to the integration of BIM with IoT and BIM with BD as the main Construction 4.0 drivers. It was found that this integration can contribute to the application of BIM itself and the whole Construction 4.0 concept since BIM is becoming the standard for the construction industry. IoT connects all necessary devices for effective monitoring of all project phases, and BD is a requirement for analyzing the huge amounts of data generated in larger construction projects. Improvements in terms of increased productivity and decreased construction duration and costs are anticipated while increasing safety. The reported synergies of BIM with Internet-linked open datasets resulted in real-time information on weather forecasts, flooding risks, population density, road congestions, waste minimization, facility management, decision making, efficient modeling, failure and damage detection, and construction site monitoring. Integration could improve the performance of real-time monitoring while increasing the quality of the entire construction project by enabling more information regarding all project phases.

This provided a basis for answering RQ4, in which the aim was to determine in which phases of the construction project's lifecycle the benefits of Construction 4.0 are most evident. Unfortunately, the answer to this question is still the design (preconstruction) phase, which is continuously developing and becoming more automated, as can be concluded from all the mentioned applications of Construction 4.0 technologies in the construction industry in this paper, while the construction phase still lags behind in terms of its implementation. It is uncertain whether this will change despite the numerous possibilities that BIM offers since the construction industry is resistant to change and does not easily give up established traditional practices. However, BIM is arguably adopting Construction 4.0 requirements and as such could be recognized as BIM 4.0.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Berger, R. *Digitization in the Construction Industry: Building Europe's Road to "Construction 4.0"*; Roland Berger GMBH: Munich, Germany, 2016; p. 16.
2. Baldini, G.; Barboni, M.; Bono, F.; Delipetrev, B.; Duch Brown, N.; Fernandez Macias, E.; Gkoumas, K.; Joossens, E.; Kalpaka, A.; Nepelski, D. *Digital Transformation in Transport, Construction, Energy, Government and Public Administration*; Publications Office of the European Union: Luxembourg, 2019.
3. Forum, W.E. *Shaping the Future of Construction: A Breakthrough in Mindset and Technology*; World Economic Forum: Geneva, Switzerland, 2016.
4. Oesterreich, T.D.; Teuteberg, F. Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Comput. Ind.* **2016**, *83*, 121–139. [CrossRef]
5. Mêda, P.; Sousa, H.; Gonçalves, M.; Calvetti, D.; Dias, P.; Camargo, F. People, Process, Technology in Construction 4.0-Balancing Knowledge, Distrust and Motivations. In Proceedings of the 37th CIB W78 Information Technology for Construction Conference (CIB W78), São Paolo, Brazil, 18–20 August 2020; pp. 218–231.
6. Owen, R.B.; Amor, R.; Dickinson, J.; Prins, M.; Kiviniemi, A. *Research Roadmap Report-Integrated Design and Delivery Solutions (IDDS) [CIB Publication: 370]*; CIB International Council for Research and Innovation in Building and Construction: Rotterdam, The Netherlands, 2013.
7. Klinc, R.; Turk, Ž. Construction 4.0-digital transformation of one of the oldest industries. *Econ. Bus. Rev. Cent. South-East. Eur.* **2019**, *21*, 393–496.
8. Sacks, R.; Brilakis, I.; Pikas, E.; Xie, H.S.; Girolami, M. Construction with digital twin information systems. *Data Cent. Eng.* **2020**, *1*, e1.
9. Boton, C.; Rivest, L.; Ghnaya, O.; Chouchen, M. What is at the Root of Construction 4.0: A systematic review of the recent research effort. *Arch. Comput. Methods Eng.* **2021**, *28*, 2331–2350. [CrossRef]
10. Arrotéia, A.V.; Freitas, R.C.; Melhado, S.B. Barriers to BIM adoption: A case study in Brazil. *Front. Built Environ.* **2021**, *7*, 16. [CrossRef]
11. Cao, Y.; Zhang, L.; McCabe, B.; Shahi, A. The benefits of and barriers to BIM adoption in Canada. In Proceedings of the ISARC International Symposium on Automation and Robotics in Construction 2019, Banff, AB, Canada, 21–24 May 2019; pp. 152–158.
12. Chan, D.W.; Olawumi, T.O.; Ho, A.M. Perceived benefits of and barriers to Building Information Modelling (BIM) implementation in construction: The case of Hong Kong. *J. Build. Eng.* **2019**, *25*, 100764. [CrossRef]
13. Charef, R.; Emmitt, S.; Alaka, H.; Fouchal, F. Building information modelling adoption in the European Union: An overview. *J. Build. Eng.* **2019**, *25*, 100777. [CrossRef]
14. Doan, D.T.; GhaffarianHoseini, A.; Naismith, N.; Ghaffarianhoseini, A.; Zhang, T.; Tookey, J. Examining critical perspectives on building information modelling (BIM) adoption in New Zealand. *Smart Sustain. Built Environ.* **2020**. ahead-of-print. [CrossRef]
15. Zhou, Y.; Yang, Y.; Yang, J.-B. Barriers to BIM implementation strategies in China. *Eng. Constr. Archit. Manag.* **2019**, *26*, 554–574. [CrossRef]
16. Ragab, M.A.; Marzouk, M. BIM Adoption in Construction Contracts: Content Analysis Approach. *J. Constr. Eng. Manag.* **2021**, *147*, 04021094. [CrossRef]
17. ISO 19650-1:2018 Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM)—Information Management Using Building Information Modelling—Part 1: Concepts and Principles. Available online: https://www.iso.org/standard/68078.html (accessed on 2 July 2021).
18. ISO 19650-2:2018 Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM)—Information Management Using Building Information Modelling—Part 2: Delivery Phase of the Assets. Available online: https://www.iso.org/standard/68080.html (accessed on 2 July 2021).
19. ISO 19650-3:2020 Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM)—Information Management Using Building Information Modelling—Part 3: Operational Phase of the Assets. Available online: https://www.iso.org/standard/75109.html (accessed on 2 July 2021).
20. ISO/DIS 19650-4 Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM)—Information Management Using Building Information Modelling—Part 4: Information Exchange. Available online: https://www.iso.org/standard/78246.html (accessed on 2 July 2021).
21. ISO 19650-5:2020 Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM)—Information Management Using Building Information Modelling—Part 5: Security-Minded Approach to Information Management. Available online: https://www.iso.org/standard/74206.html (accessed on 2 July 2021.).
22. ISO/AWI 19650-6 Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM)—Information Management Using Building Information Modelling—Part 6: Health and Safety. Available online: https://www.iso.org/standard/82705.html (accessed on 2 July 2021).
23. VOSviewer. Available online: https://www.vosviewer.com/ (accessed on 15 January 2021).
24. Roberts, B.H. The third industrial revolution: Implications for planning cities and regions. *Work. Pap. Urban Front* **2015**, *1*, 1.

25. Fitzsimmons, J. Information technology and the third industrial revolution. *Electron. Libr.* **1994**, *12*, 295–297. [CrossRef]

26. Troxler, P. Making the third industrial revolution—the struggle for polycentric structures and a new peer-production commons in the FabLab community. In *Fablabs: Of Machines, Makers and Inventors*; Walter-Herrman, J., Büching, C., Eds.; Transcript Verlag: Bielefield, Germany, 2013; pp. 181–198.

27. Anderson, C. *Makers: The New Industrial Revolution*; Random House: New York, NY, USA, 2012.

28. Finkelstein, J.; Newman, D. The third industrial revolution: A special challenge to managers. *Organ. Dyn.* **1984**, *13*, 53–65. [CrossRef]

29. Kaplinsky, R. 'Technological revolution'and the international division of labour in manufacturing: A place for the Third World? *Eur. J. Dev. Res.* **1989**, *1*, 5–37. [CrossRef]

30. Smith, B.L. The third industrial revolution: Policymaking for the Internet. *Columbia Sci. Technol. Law Rev.* **2001**, *3*, 1.

31. Musso, S. *Labor in the Third Industrial Revolution: A Tentative Synthesis*; Cambridge University Press: Cambridge, UK, 2013.

32. Brucker Juricic, B.; Galic, M.; Marenjak, S. Review of the Construction Labour Demand and Shortages in the EU. *Buildings* **2021**, *11*, 17. [CrossRef]

33. Schwab, K. *The Fourth Industrial Revolution*, 1st ed.; Currency Books: New York, NY, USA, 2017.

34. Sawhney, A.; Riley, M.; Irizarry, J. *Construction 4.0: An Innovation Platform for the Built Environment*; Routledge: London, UK, 2020.

35. Kolberg, D.; Zühlke, D. Lean automation enabled by industry 4.0 technologies. *IFAC PapersOnLine* **2015**, *48*, 1870–1875. [CrossRef]

36. Zhou, K.; Liu, T.; Zhou, L. Industry 4.0: Towards future industrial opportunities and challenges. In Proceedings of the 2015 12th International Conference on Fuzzy Systems and Knowledge Discovery (FSKD), Zhangjiajie, China, 15–17 August 2015; pp. 2147–2152.

37. Petrillo, A.; De Felice, F.; Cioffi, R.; Zomparelli, F. Fourth industrial revolution: Current practices, challenges, and opportunities. In *Digital Transformation in Smart Manufacturing*, 1st ed.; Petrillo, A., De Felice, F., Cioffi, Eds.; Intech Open Limited: London, UK, 2018; pp. 1–20. [CrossRef]

38. Lee, J.; Bagheri, B.; Kao, H.-A. A cyber-physical systems architecture for industry 4.0-based manufacturing systems. *Manuf. Lett.* **2015**, *3*, 18–23. [CrossRef]

39. Tao, F.; Qi, Q.; Wang, L.; Nee, A. Digital twins and cyber–physical systems toward smart manufacturing and industry 4.0: Correlation and comparison. *Engineering* **2019**, *5*, 653–661. [CrossRef]

40. Bloem, J.; Van Doorn, M.; Duivestein, S.; Excoffier, D.; Maas, R.; Van Ommeren, E. *The Fourth Industrial Revolution*; LINE UP Boek en Media bv: Groningen, The Netherlands, 2014; pp. 11–15.

41. Kagermann, H.; Wahlster, W.; Helbig, J. *Recommendations for Implementing the Strategic Initiative Industrie 4.0: Final Report of the Industrie 4.0 Working Group*; Forcschungsunion: Acatech, Germany, 2013; pp. 5–78.

42. MacDougall, W. *Industrie 4.0: Smart Manufacturing for the Future*; Germany Trade & Invest: Berlin, Germany, 2014.

43. Atzori, L.; Iera, A.; Morabito, G. The internet of things: A survey. *Comput. Netw.* **2010**, *54*, 2787–2805. [CrossRef]

44. Jovović, I.; Husnjak, S.; Forenbacher, I.; Maček, S. Innovative application of 5G and blockchain technology in industry 4.0. *EAI Endorsed Trans. Ind. Netw. Intell. Syst.* **2019**, *6*, 6. [CrossRef]

45. Dopico, M.; Gómez, A.; De la Fuente, D.; García, N.; Rosillo, R.; Puche, J. A vision of industry 4.0 from an artificial intelligence point of view. In Proceedings of the Proceedings on the International Conference on Artificial Intelligence (ICAI), Las Vegas, NV, USA, 25–27 July 2016; p. 407.

46. Manyika, J.; Chui, M.; Brown, B.; Bughin, J.; Dobbs, R.; Roxburgh, C.; Hung Byers, A. *Big Data: The Next Frontier for Innovation, Competition, and Productivity*; McKinsey Global Institute: New York, NY, USA, 2011.

47. Fernández, A.; Del Río, S.; López, V.; Bawakid, A.; Del Jesus, M.J.; Benítez, J.M.; Herrera, F. Big Data with Cloud Computing: An insight on the computing environment, MapReduce, and programming frameworks. *Wiley Interdiscip. Rev. Data Min. Knowl. Discov.* **2014**, *4*, 380–409. [CrossRef]

48. Purcell, B.M. Big data using cloud computing. *J. Technol. Res.* **2014**, *5*, 1.

49. Lindemann, C.; Jahnke, U.; Moi, M.; Koch, R. Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing. In Proceedings of the 23th Annual International Solid Freeform Fabrication Symposium–An Additive Manufacturing Conference, Austin, TX, USA, 6–8 August 2012.

50. Forcael, E.; Ferrari, I.; Opazo-Vega, A.; Pulido-Arcas, J.A. Construction 4.0: A Literature Review. *Sustainability* **2020**, *12*, 9755. [CrossRef]

51. Dallasega, P.; Rauch, E.; Linder, C. Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review. *Comput. Ind.* **2018**, *99*, 205–225. [CrossRef]

52. García de Soto, B.; Agustí-Juan, I.; Joss, S.; Hunhevicz, J. Implications of Construction 4.0 to the workforce and organizational structures. *Int. J. Constr. Manag.* **2019**, *19*, 1–13. [CrossRef]

53. Rowsell-Jones, A.; Lowendahl, J.; Howard, C.; Nielsen, T. *The 2017 CIO Agenda: Seize the Digital Ecosystem Opportunity*; Gartner Inc: Stamford, CT, USA, 2016.

54. Sawhney, A.; Riley, M.; Irizarry, J.; Pérez, C.T. A proposed framework for Construction 4.0 based on a review of literature. *EPiC Ser. Built Environ.* **2020**, *1*, 301–309.

55. Digital Supply Chains—Data Driven Collaboration. Available online: https://www.gs1.org/sites/default/files/digitalsupplychainsdatadrivencollaboration.pdf (accessed on 5 June 2021).

56. Cooper, S. Civil engineering collaborative digital platforms underpin the creation of 'digital ecosystems'. *Civ. Eng.* **2018**, *171*, 1. [CrossRef]

57. Hossain, M.A.; Nadeem, A. Towards digitizing the construction industry: State of the art of construction 4.0. In Proceedings of the 10th International Structural Engineering and Construction Conference, Chicago, IL, USA, 1 April 2019.

58. Anumba, C.J.; Akanmu, A.; Yuan, X.; Kan, C. Cyber—physical systems development for construction applications. *Front. Eng. Manag.* **2021**, *8*, 72–87. [CrossRef]

59. Smith, P. BIM & the 5D project cost manager. *Procedia Soc. Behav. Sci.* **2014**, *119*, 475–484.

60. Trappey, A.J.; Trappey, C.V.; Govindarajan, U.H.; Chuang, A.C.; Sun, J.J. A review of essential standards and patent landscapes for the Internet of Things: A key enabler for Industry 4.0. *Adv. Eng. Inform.* **2017**, *33*, 208–229. [CrossRef]

61. Trotta, D.; Garengo, P. Industry 4.0 key research topics: A bibliometric review. In Proceedings of the 2018 7th International Conference on Industrial Technology and Management (ICITM), Oxford, UK, 7–9 March 2018; IEEE: Oxford, UK, 2018; pp. 113–117.

62. Sardroud, J.M. Influence of RFID technology on automated management of construction materials and components. *Sci. Iran.* **2012**, *19*, 381–392. [CrossRef]

63. Maskuriy, R.; Selamat, A.; Ali, K.N.; Maresova, P.; Krejcar, O. Industry 4.0 for the construction industry—How ready is the industry? *Appl. Sci.* **2019**, *9*, 2819. [CrossRef]

64. Perrier, N.; Bled, A.; Bourgault, M.; Cousin, N.; Danjou, C.; Pellerin, R.; Roland, T. Construction 4.0: A survey of research trends. *J. Inf. Technol. Constr. (ITcon)* **2020**, *25*, 416–437. [CrossRef]

65. Newman, C.; Edwards, D.; Martek, I.; Lai, J.; Thwala, W.D.; Rillie, I. Industry 4.0 deployment in the construction industry: A bibliometric literature review and UK-based case study. *Smart Sustain. Built Environ.* **2020**. [CrossRef]

66. Digitalisation in the Construction Sector. Available online: https://ec.europa.eu/docsroom/documents/45547?locale=pt (accessed on 5 June 2021).

67. Dillon, T.S.; Zhuge, H.; Wu, C.; Singh, J.; Chang, E. Web-of-things framework for cyber–physical systems. *Concurr. Comput. Pract. Exp.* **2011**, *23*, 905–923. [CrossRef]

68. Chen, N.; Xiao, C.; Pu, F.; Wang, X.; Wang, C.; Wang, Z.; Gong, J. Cyber-physical geographical information service-enabled control of diverse in-situ sensors. *Sensors* **2015**, *15*, 2565–2592. [CrossRef]

69. Shelden, D. Cyber-physical systems and the built environment. *Technol. Archit. Des.* **2018**, *2*, 137–139. [CrossRef]

70. Xia, F.; Vinel, A.; Gao, R.; Wang, L.; Qiu, T. Evaluating IEEE 802.15. 4 for cyber-physical systems. *EURASIP J. Wirel. Commun. Netw.* **2011**, *2011*, 1–14. [CrossRef]

71. Bordel, B.; Alcarria, R.; Robles, T.; Martín, D. Cyber–physical systems: Extending pervasive sensing from control theory to the Internet of Things. *Pervasive Mob. Comput.* **2017**, *40*, 156–184. [CrossRef]

72. Kim, S.; Irizarry, J. Exploratory study on factors influencing UAS performance on highway construction projects: As the case of safety monitoring systems. In Proceedings of the Conference on Autonomous and Robotic Construction of Infrastructure, Ames, IA, USA, 2–3 June 2015; p. 132.

73. Yuan, X.; Anumba, C.J.; Parfitt, M.K. Cyber-physical systems for temporary structure monitoring. *Autom. Constr.* **2016**, *66*, 1–14. [CrossRef]

74. Calvetti, D.; Mêda, P.; Chichorro Gonçalves, M.; Sousa, H. Worker 4.0: The future of sensored construction sites. *Buildings* **2020**, *10*, 169. [CrossRef]

75. Correa, F.R. Cyber-physical systems for construction industry. In Proceedings of the 2018 IEEE Industrial Cyber-Physical Systems (ICPS), Saint Petersburg, Russia, 15–18 May 2018; pp. 392–397.

76. You, Z.; Feng, L. Integration of industry 4.0 related technologies in construction industry: A framework of cyber-physical system. *IEEE Access* **2020**, *8*, 122908–122922. [CrossRef]

77. Cerovsek, T. A review and outlook for a 'Building Information Model'(BIM): A multi-standpoint framework for technological development. *Adv. Eng. Inform.* **2011**, *25*, 224–244. [CrossRef]

78. Munoz-La Rivera, F.; Mora-Serrano, J.; Valero, I.; Oñate, E. Methodological-technological framework for Construction 4.0. *Arch. Comput. Methods Eng.* **2021**, *28*, 689–711. [CrossRef]

79. De Lange, P.; Bähre, B.; Finetti-Imhof, C.; Klamma, R.; Koch, A.; Oppermann, L. Socio-technical Challenges in the Digital Gap between Building Information Modeling and Industry 4.0. In Proceedings of the STPIS@ CAiSE, Essen, Germany, 13 June 2017; pp. 33–46.

80. Soust-Verdaguer, B.; Llatas, C.; García-Martínez, A. Critical review of bim-based LCA method to buildings. *Energy Build.* **2017**, *136*, 110–120. [CrossRef]

81. Tao, F.; Zhang, M. Digital twin shop-floor: A new shop-floor paradigm towards smart manufacturing. *IEEE Access* **2017**, *5*, 20418–20427. [CrossRef]

82. Megahed, N.A. Towards a theoretical framework for HBIM approach in historic preservation and management. *ArchNet Int. J. Arch. Res.* **2015**, *9*, 130–147. [CrossRef]

83. Wong, J.; Wang, X.; Li, H.; Chan, G. A review of cloud-based BIM technology in the construction sector. *J. Inf. Technol. Constr.* **2014**, *19*, 281–291.

84. Bilal, M.; Oyedele, L.O.; Qadir, J.; Munir, K.; Ajayi, S.O.; Akinade, O.O.; Owolabi, H.A.; Alaka, H.A.; Pasha, M. Big Data in the construction industry: A review of present status, opportunities, and future trends. *Adv. Eng. Inform.* **2016**, *30*, 500–521. [CrossRef]

85. Lin, J.R.; Hu, Z.Z.; Zhang, J.P.; Yu, F.Q. A natural-language-based approach to intelligent data retrieval and representation for cloud BIM. *Comput. Aided Civ. Infrastruct. Eng.* **2016**, *31*, 18–33. [CrossRef]

86. Sun, C.; Jiang, S.; Skibniewski, M.J.; Man, Q.; Shen, L. A literature review of the factors limiting the application of BIM in the construction industry. *Technol. Econ. Dev. Econ.* **2017**, *23*, 764–779. [CrossRef]

87. Barak, R.; Jeong, Y.-S.; Sacks, R.; Eastman, C. Unique requirements of building information modeling for cast-in-place reinforced concrete. *J. Comput. Civ. Eng.* **2009**, *23*, 64–74. [CrossRef]

88. Post, N. Building Information modeling: Snags don't dampen spirit. In *Engineering News Record, December (01)*; Manhattan: New York, NY, USA, 2008; pp. 30–32.

89. Chowdhury, T.; Adafin, J.; Wilkinson, S. Review of digital technologies to improve productivity of New Zealand construction industry. *J. Inf. Technol. Constr.* **2019**, *24*, 569–587.

90. Yu, C.; Xu, X.; Lu, Y. Computer-integrated manufacturing, cyber-physical systems and cloud manufacturing–concepts and relationships. *Manuf. Lett.* **2015**, *6*, 5–9. [CrossRef]

91. Delbrügger, T.; Lenz, L.T.; Losch, D.; Roßmann, J. A navigation framework for digital twins of factories based on building information modeling. In Proceedings of the 2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Limassol, Cyprus, 12–15 September 2017; pp. 1–4.

92. King, M. How Industry 4.0 and BIM Are Shaping the Future of the Construction Environment. Available online: https://www.gim-international.com/content/article/how-industry-4-0-and-bim-are-shaping-the-future-of-the-construction-environment (accessed on 3 April 2021).

93. Wang, X.; Chong, H.-Y. Setting new trends of integrated Building Information Modelling (BIM) for construction industry. *Constr. Innov.* **2015**, *15*, 2–6. [CrossRef]

94. Čuš-Babič, N.; Rebolj, D.; Nekrep-Perc, M.; Podbreznik, P. Supply-chain transparency within industrialized construction projects. *Comput. Ind.* **2014**, *65*, 345–353. [CrossRef]

95. Ma, Z.; Ren, Y. Integrated application of BIM and GIS: An overview. *Procedia Eng.* **2017**, *196*, 1072–1079. [CrossRef]

96. Irizarry, J.; Karan, E.P.; Jalaei, F. Integrating BIM and GIS to improve the visual monitoring of construction supply chain management. *Autom. Constr.* **2013**, *31*, 241–254. [CrossRef]

97. Meadati, P.; Irizarry, J.; Akhnoukh, A.K. BIM and RFID integration: A pilot study. In Proceedings of the Second International Conference on Construction in Developing Countries (ICCIDC-II) Advancing and Integrating Construction Education, Research and Practice, Cairo, Egypt, 3–5 August 2010; pp. 570–578.

98. Li, C.Z.; Zhong, R.Y.; Xue, F.; Xu, G.; Chen, K.; Huang, G.G.; Shen, G.Q. Integrating RFID and BIM technologies for mitigating risks and improving schedule performance of prefabricated house construction. *J. Clean. Prod.* **2017**, *165*, 1048–1062. [CrossRef]

99. Costin, A.; Pradhananga, N.; Teizer, J. Passive RFID and BIM for real-time visualization and location tracking. In Proceedings of the Construction Research Congress 2014: Construction in a Global Network, Atlanta, GA, USA, 19–21 May 2014; pp. 169–178.

100. Guo, H.; Yu, Y.; Liu, W.; Zhang, W. Integrated appliation of BIM and RFID in construction safety manangment. *J. Eng. Manag.* **2014**, *28*, 87–92.

101. Machado, R.L.; Vilela, C. Conceptual framework for integrating BIM and augmented reality in construction management. *J. Civ. Eng. Manag.* **2020**, *26*, 83–94. [CrossRef]

102. Wang, X.; Love, P.E.; Kim, M.J.; Park, C.-S.; Sing, C.-P.; Hou, L. A conceptual framework for integrating building information modeling with augmented reality. *Autom. Constr.* **2013**, *34*, 37–44. [CrossRef]

103. Wang, X.; Truijens, M.; Hou, L.; Wang, Y.; Zhou, Y. Integrating Augmented Reality with Building Information Modeling: Onsite construction process controlling for liquefied natural gas industry. *Autom. Constr.* **2014**, *40*, 96–105. [CrossRef]

104. Wang, J.; Sun, W.; Shou, W.; Wang, X.; Wu, C.; Chong, H.-Y.; Liu, Y.; Sun, C. Integrating BIM and LiDAR for real-time construction quality control. *J. Intell. Robot. Syst.* **2015**, *79*, 417–432. [CrossRef]

105. Tan, Y.; Li, S.; Wang, Q. Automated Geometric Quality Inspection of Prefabricated Housing Units Using BIM and LiDAR. *Remote. Sens.* **2020**, *12*, 2492. [CrossRef]

106. Williams, G.; Gheisari, M.; Chen, P.-J.; Irizarry, J. BIM2MAR: An efficient BIM translation to mobile augmented reality applications. *J. Manag. Eng.* **2015**, *31*, A4014009. [CrossRef]

107. Hahanov, V. *Cyber Physical Computing for IoT-Driven Services*; Springer: Berlin, Germany, 2018.

108. Kumar, S.A.; Vealey, T.; Srivastava, H. Security in internet of things: Challenges, solutions and future directions. In Proceedings of the 2016 49th Hawaii International Conference on System Sciences (HICSS), Koloa, HI, USA, 5–8 January 2016; pp. 5772–5781.

109. Ning, H.-S.; Xu, Q.-Y. Research on global Internet of Things' developments and it's construction in China. *Dianzi Xuebao (Acta Electron. Sin.)* **2010**, *38*, 2590–2599.

110. Gubbi, J.; Buyya, R.; Marusic, S.; Palaniswami, M. Internet of Things (IoT): A vision, architectural elements, and future directions. *Future Gener. Comput. Syst.* **2013**, *29*, 1645–1660. [CrossRef]

111. Wei, C.; Li, Y. Design of energy consumption monitoring and energy-saving management system of intelligent building based on the Internet of things. In Proceedings of the 2011 International Conference on Electronics, Communications and Control (ICECC), Ningbo, China, 9–11 September 2011; pp. 3650–3652.

112. Gamil, Y.; Abdullah, M.A.; Abd Rahman, I.; Asad, M.M. Internet of things in construction industry revolution 4.0. *J. Eng. Des. Technol.* **2020**, *18*, 5. [CrossRef]

113. Da Costa, K.A.; Papa, J.P.; Lisboa, C.O.; Munoz, R.; De Albuquerque, V.H.C. Internet of Things: A survey on machine learning-based intrusion detection approaches. *Comput. Netw.* **2019**, *151*, 147–157. [CrossRef]

114. Kouicem, D.E.; Bouabdallah, A.; Lakhlef, H. Internet of things security: A top-down survey. *Comput. Netw.* **2018**, *141*, 199–221. [CrossRef]

115. Hassan, W.H. Current research on Internet of Things (IoT) security: A survey. *Comput. Netw.* **2019**, *148*, 283–294.

116. Dave, B.; Buda, A.; Nurminen, A.; Främling, K. A framework for integrating BIM and IoT through open standards. *Autom. Constr.* **2018**, *95*, 35–45. [CrossRef]

117. Kim, S.H.; Ryu, H.G.; Kang, C.S. Development of an IoT-based construction site safety management system. In Proceedings of the International Conference on Information Science and Applications, Jeju, Korea, 27–29 April 2018; pp. 617–624.

118. Chung, W.W.S.; Tariq, S.; Mohandes, S.R.; Zayed, T. IoT-based application for construction site safety monitoring. *Int. J. Constr. Manag.* **2020**, *20*, 1–17. [CrossRef]

119. Kanan, R.; Elhassan, O.; Bensalem, R. An IoT-based autonomous system for workers' safety in construction sites with real-time alarming, monitoring, and positioning strategies. *Autom. Constr.* **2018**, *88*, 73–86. [CrossRef]

120. Park, M.; Park, S.; Song, M.; Park, S. IoT-based Safety Recognition Service for Construction Site. In Proceedings of the 2019 Eleventh International Conference on Ubiquitous and Future Networks (ICUFN), Zagreb, Croatia, 2–5 July 2019; pp. 738–741.

121. Teizer, J.; Wolf, M.; Golovina, O.; Perschewski, M.; Propach, M.; Neges, M.; König, M. Internet of Things (IoT) for integrating environmental and localization data in Building Information Modeling (BIM). In Proceedings of the International Symposium on Automation and Robotics in Construction, Taipei, Taiwan, 28–30 June 2017.

122. Chiarello, F.; Trivelli, L.; Bonaccorsi, A.; Fantoni, G. Extracting and mapping industry 4.0 technologies using wikipedia. *Comput. Ind.* **2018**, *100*, 244–257. [CrossRef]

123. Borgia, E. The Internet of Things vision: Key features, applications and open issues. *Comput. Commun.* **2014**, *54*, 1–31. [CrossRef]

124. Li, C.Z.; Xue, F.; Li, X.; Hong, J.; Shen, G.Q. An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction. *Autom. Constr.* **2018**, *89*, 146–161. [CrossRef]

125. Louis, J.; Dunston, P.S. Integrating IoT into operational workflows for real-time and automated decision-making in repetitive construction operations. *Autom. Constr.* **2018**, *94*, 317–327. [CrossRef]

126. Hand, D.J.; Adams, N.M. Data Mining. In *Wiley StatsRef: Statistics Reference Online*; Wiley: Hoboken, NJ, USA, 2014; pp. 1–7.

127. Yang, C.; Huang, Q.; Li, Z.; Liu, K.; Hu, F. Big Data and cloud computing: Innovation opportunities and challenges. *Int. J. Digit. Earth* **2017**, *10*, 13–53. [CrossRef]

128. Omran, B.A.; Chen, Q. Trend on the implementation of analytical techniques for big data in construction research (2000–2014). In Proceedings of the Construction Research Congress 2016, San Juan, Puerto Rico, 31 May–2 June 2016; pp. 990–999.

129. Katal, A.; Wazid, M.; Goudar, R.H. Big data: Issues, challenges, tools and good practices. In Proceedings of the 2013 Sixth International Conference on Contemporary Computing (IC3), Noida, India, 8–10 August 2013; pp. 404–409.

130. Cuzzocrea, A.; Bellatreche, L.; Song, I.-Y. Data warehousing and OLAP over big data: Current challenges and future research directions. In Proceedings of the Sixteenth International Workshop on Data Warehousing and OLAP, San Francisco, CA, USA, 28 October 2013; pp. 67–70.

131. Agrawal, D.; Bernstein, P.; Bertino, E.; Davidson, S.; Dayal, U.; Franklin, M.; Gehrke, J.; Haas, L.; Halevy, A.; Han, J. *Challenges and Opportunities with Big Data 2011-1*; Purdue University: West Lafayette, IN, USA, 2011.

132. Guo, S.; Ding, L.; Luo, H.; Jiang, X. A Big-Data-based platform of workers' behavior: Observations from the field. *Accid. Anal. Prev.* **2016**, *93*, 299–309. [CrossRef] [PubMed]

133. Kargah-Ostadi, N. Comparison of machine learning techniques for developing performance prediction models. In Proceedings of the Computing in Civil and Building Engineering (2014), Orlando, FL, USA, 23–25 June 2014; pp. 1222–1229.

134. Al Nuaimi, E.; Al Neyadi, H.; Mohamed, N.; Al-Jaroodi, J. Applications of big data to smart cities. *J. Internet Serv. Appl.* **2015**, *6*, 25. [CrossRef]

135. Lu, W.; Webster, C.; Peng, Y.; Chen, X.; Chen, K. Big data in construction waste management: Prospects and challenges. *Detritus* **2018**, *4*, 129–139. [CrossRef]

136. Lu, W. Big data analytics to identify illegal construction waste dumping: A Hong Kong study. *Resour. Conserv. Recycl.* **2019**, *141*, 264–272. [CrossRef]

137. Górecki, J. Big Data as a Project Risk Management Tool. In *Risk Management Treatise for Engineering Practitioners*; Intech Open Limited: London, UK, 2018.

138. Keating, S. Beyond 3D printing: The new Dimensionsof additive fabrication. In *Designing for Emerging Technologies: UX for Genomics, Robotics, and the Internet of Things*; O'Reilly: Newton, MA, USA, 2014; p. 379.

139. Hull, C.W. *Apparatus for Production of Three-Dimensional Objects by Stereolithography*. 1984. Available online: https://patents.google.com/patent/US4575330A/en (accessed on 2 July 2021).

140. Pegna, J. Exploratory investigation of solid freeform construction. *Autom. Constr.* **1997**, *5*, 427–437. [CrossRef]

141. De Schutter, G.; Lesage, K.; Mechtcherine, V.; Nerella, V.N.; Habert, G.; Agusti-Juan, I. Vision of 3D printing with concrete—technical, economic and environmental potentials. *Cem. Concr. Res.* **2018**, *112*, 25–36. [CrossRef]

142. Mehrpouya, M.; Dehghanghadikolaei, A.; Fotovvati, B.; Vosooghnia, A.; Emamian, S.S.; Gisario, A. The potential of additive manufacturing in the smart factory industrial 4.0: A review. *Appl. Sci.* **2019**, *9*, 3865. [CrossRef]

143. Ghaffar, S.H.; Corker, J.; Fan, M. Additive manufacturing technology and its implementation in construction as an eco-innovative solution. *Autom. Constr.* **2018**, *93*, 1–11. [CrossRef]

144. Khoshevis, B. *Additive Fabrication Apparatus and Method*. 1996. Available online: https://patents.google.com/patent/US5529471A/en (accessed on 2 July 2021).

145. Halicioglu, F.H.; Koralay, S. Applicability analysis of additive manufacturing methods in construction projects. *Gradevinar* **2020**, *72*, 335–349.

146. International, A. F2792-12a-Standard Terminology for Additive Manufacturing Technologies. *Rapid Manuf. Assoc.* **2013**, *12*, 10–12.

147. International Organization for Standardization. *Additive Manufacturing: General: Principles: Terminology*; International Organization for Standardization: Geneva, Switzerland, 2015.

148. Al Rashid, A.; Khan, S.A.; Al-Ghamdi, S.G.; Koç, M. Additive manufacturing: Technology, applications, markets, and opportunities for the built environment. *Autom. Constr.* **2020**, *118*, 103268. [CrossRef]

149. Krupík, P. 3D printers as part of Construction 4.0 with a focus on transport constructions. In Proceedings of the IOP Conference Series: Materials Science and Engineering, High Tatras, Slovakia, 23–24 April 2020; p. 012025.

150. Cor, A. The First on-Site House Has Been Printed in Russia. Available online: http://apiscor.com/en/about/news/first-house (accessed on 20 February 2017).

151. Sevenson, B. Shanghai-Based WinSun 3D Prints 6-Story Apartment Building and an Incredible home. Available online: https://www.b3d-online.com/blog-news/shanghai-based-winsun-3d-prints-6-story-apartment-building-and-an-incredible-home (accessed on 20 February 2017).

152. Labonnote, N.; Rønnquist, A.; Manum, B.; Rüther, P. Additive construction: State-of-the-art, challenges and opportunities. *Autom. Constr.* **2016**, *72*, 347–366. [CrossRef]

153. Camacho, D.D.; Clayton, P.; O'Brien, W.J.; Seepersad, C.; Juenger, M.; Ferron, R.; Salamone, S. Applications of additive manufacturing in the construction industry–A forward-looking review. *Autom. Constr.* **2018**, *89*, 110–119. [CrossRef]

154. Correa, F. Is BIM big enough to take advantage of big data analytics? In Proceedings of the International Symposium on Automation and Robotics in Construction (ISARC), Oulu, Finland, 15–18 June 2015; p. 1.

155. Lu, W.; Lai, C.C.; Tse, T. *BIM and Big Data for Construction Cost Management*; Routledge: London, UK, 2018.

156. Eadie, R.; Browne, M.; Odeyinka, H.; McKeown, C.; McNiff, S. BIM implementation throughout the UK construction project lifecycle: An analysis. *Autom. Constr.* **2013**, *36*, 145–151. [CrossRef]

157. Liu, H.; Al-Hussein, M.; Lu, M. BIM-based integrated approach for detailed construction scheduling under resource constraints. *Autom. Constr.* **2015**, *53*, 29–43. [CrossRef]

158. Wang, Y.; Wang, X.; Wang, J.; Yung, P.; Jun, G. Engagement of facilities management in design stage through BIM: Framework and a case study. *Adv. Civ. Eng.* **2013**, *2013*, 1–8. [CrossRef]

159. Curry, E.; O'Donnell, J.; Corry, E.; Hasan, S.; Keane, M.; O'Riain, S. Linking building data in the cloud: Integrating cross-domain building data using linked data. *Adv. Eng. Inform.* **2013**, *27*, 206–219. [CrossRef]

160. Galić, M.; Nguyen Vu, L.; Feine, I. Weather Forecast as an Additional Dimension to BIM. In Proceedings of the 12th International Conference Organization, Technology And Management in Construction Conference Proceedings, Primošten, Croatia, 2–5 September 2015; p. 355.

161. Bilal, M.; Oyedele, L.O.; Qadir, J.; Munir, K.; Akinade, O.O.; Ajayi, S.O.; Alaka, H.A.; Owolabi, H.A. Analysis of critical features and evaluation of BIM software: Towards a plug-in for construction waste minimization using big data. *Int. J. Sustain. Build. Technol. Urban Dev.* **2015**, *6*, 211–228. [CrossRef]

162. Aziz, Z.; Riaz, Z.; Arslan, M. Leveraging BIM and big data to deliver well maintained highways. *Facilities* **2017**, *35*, 818–832. [CrossRef]

163. Ibrahim, K.; Abanda, H.; Vidalakis, C.; Wood, G. Bim big data system architecture for asset management: A conceptual framework. In Proceedings of the Joint Conference on Computing in Construction (JC3), Heriot-Watt University School of the Built Environment, Edinburgh, Scotland, 21 July 2017; pp. 289–296.

164. Chen, H.-M.; Chang, K.-C.; Lin, T.-H. A cloud-based system framework for performing online viewing, storage, and analysis on big data of massive BIMs. *Autom. Constr.* **2016**, *71*, 34–48. [CrossRef]

165. Gbadamosi, A.-Q.; Oyedele, L.; Mahamadu, A.-M.; Kusimo, H.; Bilal, M.; Delgado, J.M.D.; Muhammed-Yakubu, N. Big data for Design Options Repository: Towards a DFMA approach for offsite construction. *Autom. Constr.* **2020**, *120*, 103388. [CrossRef]

166. Venkrbec, V.; Galić, M.; Klanšek, U. Construction process optimisation–review of methods, tools and applications. *Građevinar* **2018**, *70*, 593–606.

167. Bottaccioli, L.; Aliberti, A.; Ugliotti, F.; Patti, E.; Osello, A.; Macii, E.; Acquaviva, A. Building energy modelling and monitoring by integration of IoT devices and building information models. In Proceedings of the 2017 IEEE 41st Annual Computer Software and Applications Conference (COMPSAC), Turin, Italy, 4–8 July 2017; pp. 914–922.

168. Tagliabue, L.C.; Ciribini, A.L.C. A BIM-Based IoT Approach to the Construction Site Management. *IN_BO. Ric. E Progett. Per Il Territ. Città E L'architettura* **2018**, *9*, 136–145.

169. Wu, C.-M.; Liu, H.-L.; Huang, L.-M.; Lin, J.-F.; Hsu, M.-W. Integrating BIM and IoT technology in environmental planning and protection of urban utility tunnel construction. In Proceedings of the 2018 IEEE International Conference on Advanced Manufacturing (ICAM), Yunlin, Taiwan, 16–18 November 2018; pp. 198–201.

170. Sava, G.N.; Pluteanu, S.; Tanasiev, V.; Patrascu, R.; Necula, H. Integration of BIM solutions and IoT in smart houses. In Proceedings of the 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Palermo, Italy, 12–15 June 2018; pp. 1–4.

171. Tang, S.; Shelden, D.R.; Eastman, C.M.; Pishdad-Bozorgi, P.; Gao, X. A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends. *Autom. Constr.* **2019**, *101*, 127–139. [CrossRef]

172. Wu, I.; Liu, C.-C. A visual and persuasive energy conservation system based on BIM and IoT technology. *Sensors* **2020**, *20*, 139. [CrossRef]