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Perspective

Digital Technologies in Offsite and Prefabricated Construction: Theories and Applications

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Abstract: Due to its similarity to industrialized products, the offsite construction industry is seen as a focus for the transformation of Construction 4.0. Many digital technologies have been applied or have the potential to be applied to realize the integration of design, manufacturing, and assembly. The main objective of this review was to identify the current stage of applying digital technologies in offsite construction. In this review, 171 related papers from the last 10 years (i.e., 2013–2022) were obtained by collecting and filtering them. They were classified and analyzed according to the digital twin concept, application areas, and specific application directions. The results indicated that there are apparent differences in the utilization and development level of different technologies in different years. Meanwhile, the introduction, current stages, and benefits of different digital technologies are also discussed. Finally, this review summarizes the current popular fields and speculates on future research directions by analyzing article publication trends, which sheds light on future research.

Keywords: building information modeling (BIM); design for manufacturing and assembly (DfMA); digital technologies; offsite construction; supply chain management (SCM)

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1. Introduction

Offsite construction refers to the practice of producing construction components in the manufacturing factory, shipping complete components or semi-components to construction sites, and finally assembling the components to create buildings. It may also be named prefabricated construction, industrialized building, etc. [1,2], with subtle differences in various contexts. According to the degree of modularization and the prefabricated unit, prefabrication encompasses two main construction methods: panelized and modular. The panelized technique is a construction technique that utilizes wall panels manufactured in a controlled environment, transported to the construction site, and installed on the prepared foundation. The modular technique is "partially built in a plant, shipped to a development site, and placed on a foundation, where the roof structure and exterior finishes are completed" [3]. The fundamental difference between these two is the prefabricated unit, which for the first are structural panels and for the second are complete box-like modules, including the roof structure and exterior finishes and which sometimes represent the functional units of the home. These two construction approaches are usually chosen based on site conditions, building scale and style, client needs, etc. [4]. In the traditional construction industry, one project is usually delivered through decentralized processes, involving many stakeholders, such as different contractors or subcontractors with different detailed functions who tend to "do their own thing" rather than collaborate with each other and are involved (e.g., design, procurement, concrete pouring, stud assembly, finishing, and so on) [5]. Thus, participants of the same project tend to be relatively fragmented, with a lack of communication, collaboration, and integration among parties [6]. This dispersion of construction industry participants has led to major issues, such as the waste of resources and labor, repetitive work, cost increases, schedule delays, and even safety risks [7]. Conventional construction methods are normally labor intensive, produce high volumes of construction waste, and have lower efficiency [8]. In contrast, offsite construction has attracted great attention from both scholars and practitioners because of its advantages [9]. It is seen as an alternative and novel construction technique and has emerged as a promising construction method to address traditional onsite construction challenges such as labor, energy, wastage, pollution, speed of delivery, productivity, quality, safety, and promoting sustainable construction [10].

Construction sites have seen much progress and have benefited from the uptake of new technologies. However, such advances have been in the areas of building methods, materials, plants, and machinery. Even with such progressive changes, the productivity rates in the construction sector are still the lowest in the industry [11]. Turner et al. [11] concluded the following reasons: (1) skill requirements needed for entry into the construction industry are reduced, while construction professionals face a shortage, leading to a low per-person increase in productivity; (2) increasing complexity in the onsite construction projects. In addition, due to poor productivity, skill shortages, and the complexity of projects, as the consumption of labor, natural resources (e.g., cement, sand, gravel), and fossil resources (e.g., diesel and petrol for machinery and transportation) increase, so does the total construction cost, resulting in poor sustainability. There is, therefore, a need to use digital technologies to extract useful project-related information and to simplify the complexity of projects to better guide practitioners in their work, along with updating digital technologies to make them easily operated, widely applicable, data-synchronized, editable, and shareable, realizing productivity increase and finally sustainable development. Currently, the construction industry is seen as one of the sectors lagging behind in the use of modern industrial digital tools [11] while, in the meantime, the manufacturing industry has successfully realized a digital transformation [12] and stepped into a new phase called "Industry 4.0" in the industrial revolution that focuses on real-time interconnectivity and automation. Industry 4.0 can be defined as the embedding of intelligent products into digital and physical processes. Digital and physical processes interact with each other and with cross-geographical and organizational boundaries [13]. The successful transformation of Industry 4.0 has reference value for the construction industry, which faces challenges such as inadequate productivity, automation, and integration [14]. The "Made Smarter UK" review identified construction as one of the sectors that could benefit from the Industry 4.0 revolution [11]. Toward this, in recent years, the worldwide construction sector has begun to adopt digital technologies in the pursuit of operational and productivity gains, termed Construction 4.0. Since first mentioned in 2016, this concept was primarily based on the awareness by construction firms of the digitization of the construction industry, adopting Industry 4.0 technologies to achieve four key concepts: digital data, automation, connectivity, and digital access [15]. It was seen as an enabling force that will usher in the evolution of the construction industry and revolutionize its practices and techniques.

One of these planning and optimization concepts with great potential in many industrial fields is the digital twin [16]. It is the virtual and computerized counterpart of a physical system. It can be used to simulate it for various purposes, exploiting a real-time synchronization of the sensed data originating from the field level, and it is able to decide between a set of actions with the focus to orchestrate and execute the whole production system in an optimal way [17–19]. The digital twin was already applied in use for Construction 4.0 and is gaining more and more attention, especially in the offsite construction industry. The reasons are: (1) Anil Sawhney et al. [20] defined Construction 4.0 as a "transformative framework", where the first transformation is "industrial production and construction" that could be interpreted as the industrialization of construction, which is defined as the process through which construction aims to improve productivity through increased mechanization and automation [21]. It requires a combination of the construction site and supply chain (factory). Offsite construction, the subject of this study, is one of the typical examples of the industrialization of construction. It could be simply divided into three major parts: design, manufacturing, and assembly, which is similar to the manufacturing industry. Therefore, the relatively mature industrial theories, frameworks, and techniques that emerged from Industry 4.0 have better applicability to offsite construction, and there is much to learn from. (2) The digital twin concept has a similarity with building information modeling (BIM). BIM technology is one of the main technologies currently used to solve inadequate preplanning and information loss during project delivery caused by the fragmentation of the construction industry. It uses 2D drafting, 3D modeling, 4D time scheduling, and 5D cost estimation [22] in a virtual information model to offer an overall plan throughout the whole project upfront, which is used throughout the entire project life cycle. Major benefits consist of design consistency and visualization, cost estimations, clash detection, implementation of lean construction, and improved stakeholder collaboration [23]. It could provide a certain amount of guidance in the early stage for the subsequent actual construction, but it does not allow for the control of the entire project cycle and real-time adjustment based on reality. Thus, BIM can be described as the "unidirectional mapping from the virtual world to the physical world at the early stage", while the digital twin is the "bidirectional mapping between virtual and physical worlds throughout the project lifecycle". It is composed of three components, which are the physical entities in the physical world, the virtual models in the virtual world, and the connected data that tie the two worlds [24]. Not only can a virtual model be created during the planning phase to provide guidance and advice for the subsequent actual construction, but various information generated during the actual production process can also be fed back and transferred to the virtual model for real-time adjustment, which could be seen as the extension of BIM. It is a dynamic process throughout the whole project lifecycle, connecting design, supply chain, and construction sites together. This theory allows the industry to become nimble in its operations and results in a more collaborative and sustainable construction eco-system.

The aim of this paper was to review the current application of digital technologies for offsite and prefabricated construction through a literature review conducted by qualitative analysis from the perspective of Construction 4.0 in terms of application areas. The paper also used quantitative analysis of the literature review and drew analogies to Industry 4.0 from a more mature industry perspective to theorize the future direction of digital technologies in order to provide theoretical recommendations for future research and technology development directions.

2. Methodology

This paper adopted a qualitative analysis, supplemented by a quantitative analysis, to review and outlook the academic research in the field of the offsite construction industry in the past decade through a literature review. The literature collection and filtering in this paper was a top-down approach: articles were searched for and collected using broad terms, and then those that were not within the scope of the study were excluded. The specific method included: (1) collecting, identifying, and filtering relevant articles; (2) further reviewing and classifying the selected articles; and (3) evaluating and analyzing the literature in groups (shown in Figure 1). The specific searching and filtering criteria used are shown in Figure 2:

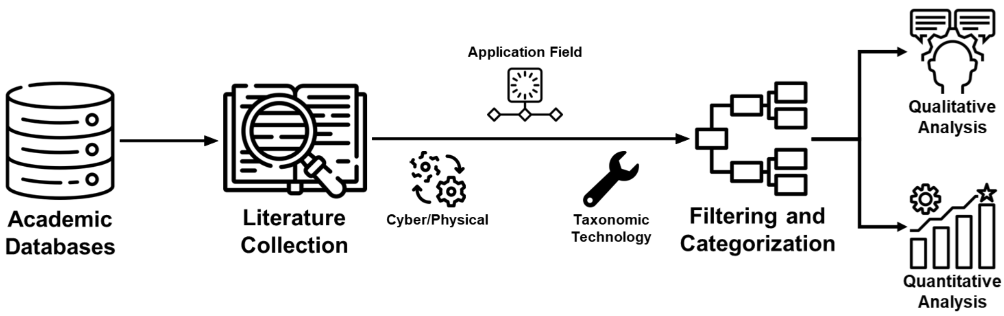

Figure 1. Methodology.

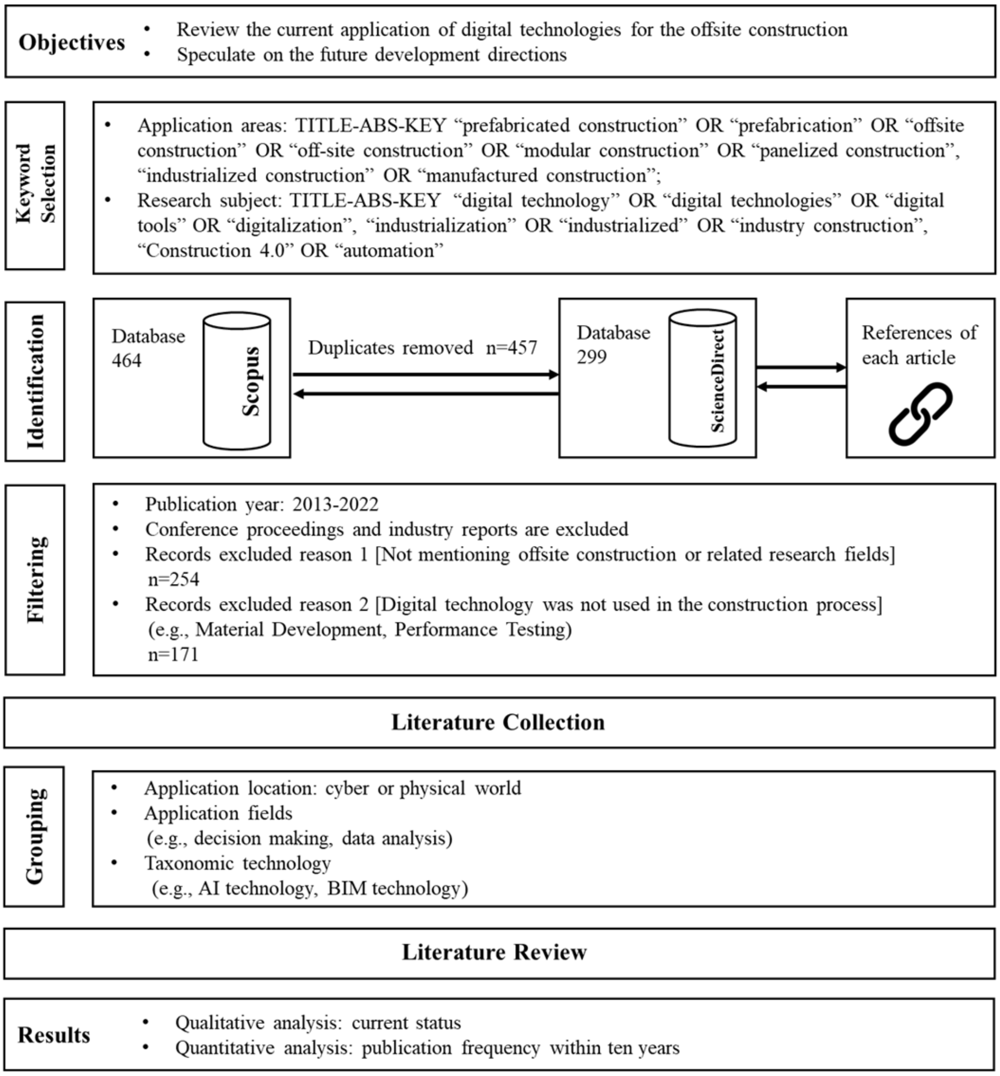

Figure 2. Research method framework.

(1) Academic databases: Two academic databases (Scopus and ScienceDirect) were selected for implementing a comprehensive search on journal papers. Articles retrieved and exported from the various databases, respectively, were compared, complemented each other, and finally, produced the literature collection. The references of each article were also applied to identify relevant articles that did not appear during searching to refine the literature review.

(2) Collection standard: A broad range of terms can be used when referring to a specific topic or concept. To search and locate all the relevant articles from the academic databases, it was necessary to create a complete combination of keywords addressing the topic [25]. This paper applied the combination of terms within titles, abstracts, and keywords in search. The first term focused on the application areas, such as "prefabricated construction", "prefabrication", "offsite construction", "off-site construction", "modular construction", "panelized construction", "industrialized construction", and "manufactured construction". The second term focused on the research subjects, such as "digital technology", "digital technologies", "digital tools", "digitalization", "industrialization", "industrialized", "industry construction", "Construction 4.0", and "automation". This research only considered peer-reviewed articles published in English in reputable construction, engineering, management, and manufacturing journals. Conference proceedings and industry reports were excluded to make sure the qualitative analysis was only conducted on mature, high quality, properly conducted

peer-reviewed research to obtain the results. This rationale was proven feasible in other literature reviews [25]. In addition, this paper focused on manufacturing and management; thus, articles related to the development of new construction materials (e.g., 3D printing reinforcement materials), material performance testing methods (e.g., bending tests, fire behavior), construction element design (e.g., column, connection), and structural design were not under consideration.

(3) Publication year: This article aimed at investigating the latest application and current challenges of digital technologies in prefabricated construction and deriving possible future research directions. Thus, only articles published in the last 10 years, namely from 2013 to 2022, were selected. Some previous articles were also selected to supplement basic knowledge and to help investigate development in some specific fields (e.g., the development of blockchain, Big data).

(4) Filtering and categorization standard: Relevant articles collected from the initial broad search results were screened and categorized. In this process, a manual review method was performed by researchers in the offsite construction industry. With the unified standard decided beforehand, the literature was primarily screened by reviewing titles, keywords, and abstracts to eliminate papers that were without the scope of this paper's target research domain, and then the remaining articles were generally classified into different categories according to their main applications locations (cyber or physical) and fields. Subsequently, the subcategorization under the main categories was conducted according to detailed technologies. It is worth noting that only those articles that contained detailed descriptions (e.g., definition, origin, common practice, research study, challenges) of an application direction were considered as belonging to that group. Verification was also completed to ensure that the groupings were reasonable.

This paper is organized into one general background literature review by qualitative analysis of the current offsite construction industry affected by Industry 4.0. The results are shown in Section 3. This article performed a quantitative analysis of the trends in the research field of the literature within a decade in Section 4 through the descriptive method, with an overall conclusion provided in Section 5.

3. Results

The research on the implementation of digital technology in the offsite construction industry was categorized through filtering and classification. As shown in Figure 3, the literature is divided into two domains, which are determined as design for manufacturing and assembly (DfMA) and supply chain management (SCM) based on the location of tasks (virtual world and physical world defined in the digital twin concept). They are composed of five main sections in total related to digital technology application areas, and these sections are further divided into subsections based on specific application directions. The five sections are: (1) DfMA, including building information modeling (BIM), virtualization, and interoperability (see Section 3.1); (2) data acquisition, including document, sensor, and monitor (see Section 3.2.1); (3) data integration, including storage and transmission (see Section 3.2.2); (4) data analysis, including descriptive analysis, diagnostic analysis, and predictive analysis (see Section 3.2.3); (5) decision-making, including manual and automatic (see Section 3.2.4). Sections two through five were designed in the expected sequence of task development that occurs in the physical world: data acquisition, integration, analysis, and finally making decisions. They are connected by a single arrow with solid lines in time order. The first section, DfMA, refers to the design and planning of the entire project through virtual models in the earliest stages in order to provide guidance for actual production. Thus, it could be seen as "data generation", ranking the first task in this paper, and it is collected by "data acquisition". Meanwhile, due to the bidirectional transmission of the digital twin, there is feedback from the physical world to DfMA afterward; data collected during manufacturing and assembly are uploaded to the virtual world; analysis and decisions based on actual conditions are also uploaded so that the virtual model can be modified and further optimized for the latest guidance. In addition, this synchronization is real-time and occurs throughout the project instead of in the time order. Therefore, the DfMA is connected with the physical world with the double arrow with dotted lines, forming the theoretically closed loop of the offsite and prefabricated construction industry.

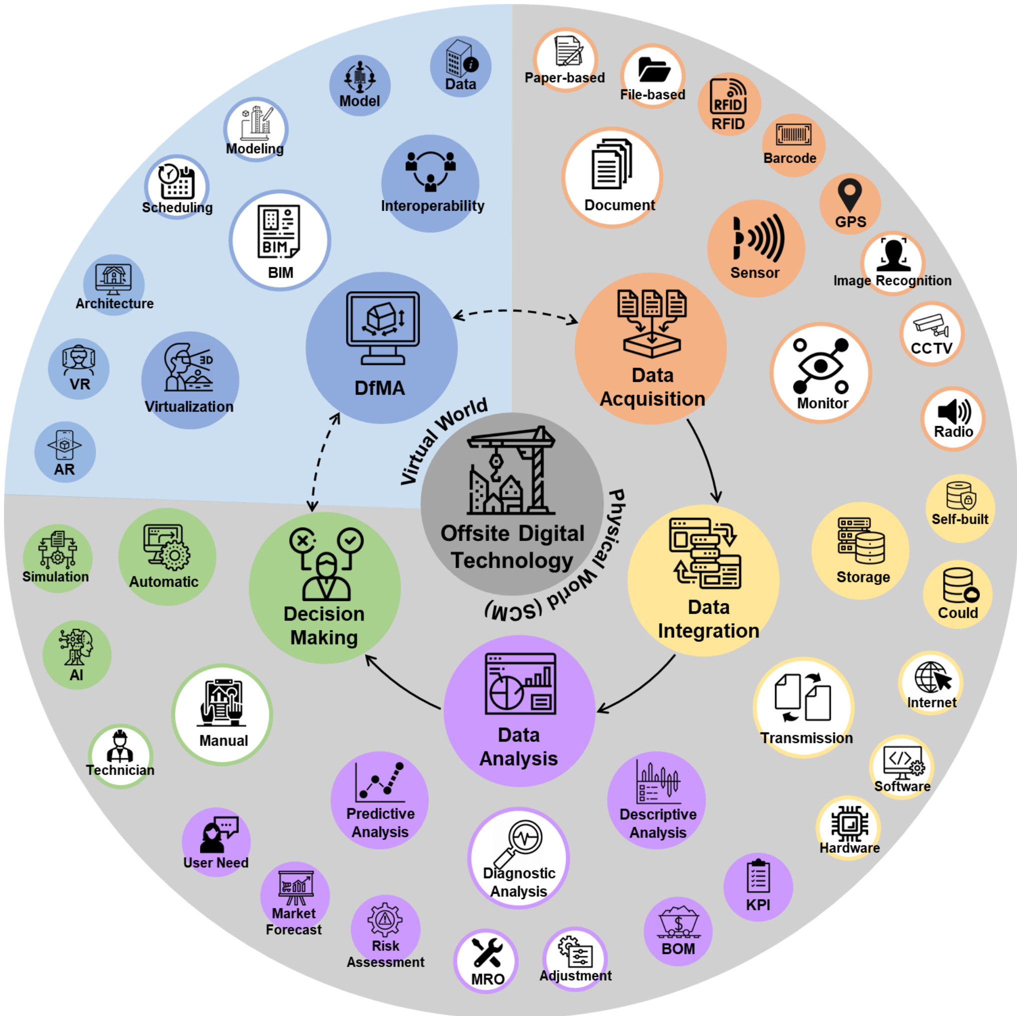

Figure 3. Digital technology for offsite construction.

3.1. Design for Manufacturing and Assembly (DfMA)

Design for Manufacturing and Assembly (DFMA) is the combination of the design for manufacturing (DfM) and the design for assembly (DfA), where DfM focuses on minimizing part counts and DfA focuses on making attachment simpler [26]. It is an engineering approach that focuses on reducing time-to-market and total production costs by prioritizing the ease of manufacturing product components and simplifying the assembly of those components in the final product by digital technologies. This process usually is conducted in the early design phase of the product life cycle [27]. As the construction industry is moving towards the combination of offsite prefabrication and onsite assembly, DfMA has gained momentum in this heterogeneous industry [28]. Its advantages in time reduction, cost reduction, quality improvement, and increased reliability have been recognized by researchers in this industry. The reason for this is that the design principle of DfMA is to help simplify the overall manufacturing and assembly process, since it is pre-considered in the module or component design, which could lead to the minimization of waste and reduction of labor costs, resulting in both time and cost reduction and ultimately achieving industrial sustainability [26]. In this paper, digital technologies used in DfMA are divided into building information modeling (BIM), interoperability, and virtualization categories according to their application.

3.1.1. BIM

BIM has become one of the most widely used digital technologies in the construction industry since it was first introduced in the early 2000s [29]. Based on traditional 2D drafting and 3D modeling, BIM allows the application of the fourth and fifth dimensions related to time and cost estimations. It is defined as the process of generating, storing, managing, exchanging, and sharing building information in an interoperable and repeatable way [5]. The model, which originally provided only the exterior and/or interior design, was given project-related information, and this information was linked to each model component one-to-one. Therefore, it has a strong ability to give an overall strategy in the early stages of the project lifecycle. In addition, over time, more BIM-based digital technologies (e.g., software, plug-ins) with better performance and specificity were developed to meet the needs of specific applications or construction-type areas. V. J. L. Gan [30] developed a novel BIM-based graph data model aimed at automating the generative design of modular buildings. It could parametrically operate the spatial attributes of volumetric modules and generate the 3D models in BIM, paving the way for evaluating the suitability of each alternative with computational methods (e.g., machine learning) toward determining a set of optimal solutions. H. Liu et al. [31] designed a BIM-based generation framework with a building information extraction tool, a generative design algorithm, and a simulation-based performance evaluation model. They successfully used it to automatically generate and evaluate various design options for panelized designs, improving productivity and installation efficiency. Cuellar Lobo et al. [32] also combined BIM models and simulation-based design algorithms to realize the automation and optimization of the drywall installation process. The improvement of planning drywall installation of this approach was proven in terms of environmental, cost, and aesthetic factors. Additionally, Bao et al. [33] developed a BIM software called "Fun Plus", which was designed and used in conjunction with Autodesk Revit to expand the understanding of DfMA and offsite technology from exterior to interior in the construction industry, integrating the interior design along with construction and the supply chain. In terms of scheduling, H. Liu et al. [34] used BIM and algorithms to enable the systematic generation of schedules, generate expected schedules for panelized construction, and assist project managers in effectively planning onsite assembly by reducing human error in scheduling for panelized construction.

3.1.2. Interoperability

As mentioned before, more and more BIM-based digital technologies are being developed and put to use to meet different industry requirements. This leads to a problem: files from different digital technologies by various stakeholders are poorly compatible and may not be read successfully or may have missing components regarding input/output. Currently, there are two ways to improve interoperability. The first one is to use a shareable platform accessible to stakeholders to give feedback (e.g., Revizto, BIM 360). However, this approach does not allow for full interoperability. Instead, it takes feedback from others into account to modify BIM models within the same file format. The second one is to use file attributes compatible with multiple software to enhance interoperability. The Industry Foundation Classes (IFC) file with a unified database is one viable approach to delivering visible geometric representation and background engineering information [30,35–37]. Moreover, different from the internal interoperability within virtual design, the communication between virtual and physical worlds is also an important part of the realization of DfMA interoperability. The original purpose of DfMA can only be achieved if manufacturing and assembly are compliant with the design requirement and can provide feedback to achieve the real-time synchronization and modification of the design plan. Sun and Kim [38] proposed a national real-time updated standard BIM library where BIM modular objects are directly connected to modular products in reality to improve design and manufacturing productivity. This library allows designers and suppliers to connect without the difficulties caused by territorial disparity (e.g., different regional regulations, cross-regional modular supply) and is considered a viable way to achieve integrated project delivery (IPD). Nowadays, with the rapid development of digital technology, on the basis of BIM, many new technologies are cited to achieve interoperability. Lu, et al. [39] built an IoT-BIM platform that ties virtual models to offsite production management to provide better information visibility, traceability, and a more cooperative working environment.

3.1.3. Virtualization

For humans, an important method of interacting with information is via reliance on communication through the spatial medium. The construction industry is inherently linked to the spatial environment and needs the provision of delivering information in multi-dimensional space to enhance the market [40]. Traditional 2D drafts and 3D models (including BIM models) have the ability to present architectural designs to stakeholders, but with the development of digital visualization technologies, people demand a higher level of engagement (e.g., walkability). The development of immersive technologies (ImTs) in recent years has provided a solution to this glitch by providing a platform for different stakeholders to be fully immersed during various phases of the project [41]. Virtual reality (VR) and augmented reality (AR) are two common ImTs that are highly prominent in the construction industry, making the user experience more interactive and realistic. They imitate the real world or merge with it through a digital medium to provide a sense of immersion, making the user's experience more interactive and realistic and to have a better understanding of the outcome [42,43]. VR is a digital mimicry experienced by the user to visualize virtual content by immersing a person in a virtual domain environment to interact with 3D models generated by computers [44]. Game engines are the most common practice for preparing virtual environments. Ezzeddine and García de Soto [45] used Unity to create a platform to integrate the design, production, transportation, and construction teams into modular projects, visualizing the entire project lifecycle. In addition, VR can also mimic human senses, such as vision, hearing, touch, proprioception, and smell, through human–computer interactions to provide a high level of information [46]. It can be used for training and safety purposes. For example, high-risk spaces (underground construction) for construction can be turned into an immersive environment, and this provides useful information to freshly graduated students and novice practitioners [47]. Pooladvand et al. [48] developed a crane simulator system in the virtual reality (VR) environment. This interactive system evaluates the lift operation quantitatively in real-time in terms of its safety and practicability for the entire operation (entire lift path), enhancing engineered lift planning, increasing workplace awareness, and evaluating and mitigating lift-related risks. AR is described as the superimposition of the virtual world over the real world to enhance reality perception [49]. It is different from VR in augmenting the space with real and virtual information existing at the same time, where a user can interact intuitively, unlike replacing the real content, which is a drawback of VR [50]. Rather than providing a synthetic reality, AR overlays more information onto reality [51]. Ahn et al. [52] used projection-based AR technology to improve the accuracy of prefabricated walls in manufacturing and to reduce potential quality problems in the manual assembly working environment. Fazel and Izadi [53] used camera-based AR technology to determine the specific position and rotation of the modules in spatial terms. However, the user cannot interact with or manipulate the augmented objects through AR; rather, they only add the information. To solve this, mixed reality (MR) was proposed to be the combination of VR and AR, blending to form and produce new visualizations and environments. Its contribution to the production of prefabricated buildings is theoretically possible but has not been proven in concrete cases [47].

3.2. Supply Chain Management (SCM)

As construction manufacturing and assembly processes are learning from the manufacturing industry, it is a key concept for the digital transformation of the construction industry [54]. An offsite construction project is designed and built by prefabricated units. Therefore, for the manufacturing side, they need to fabricate products that meet customer specifications, which are considered "engineer-to-order products" (e.g., prefabricated light gauge steel walls). They are often characterized by the complexity of the design and the variability of the manufacturing process [55], which results in difficulty in manufacturing (quantity, quality, diversity) and progress tracking (schedule and budget). To achieve this, it requires a high level of manufacturing accuracy, productivity, production flexibility, and the ability to control and adjust in real time. In terms of the assembly side, onsite assembly is one of the most complicated and uncertain phases of a project, with the aim of installing and joining prefabricated elements as designed to form a complete building [56]. Some inherent properties of construction (e.g., variability of outside conditions, geographic dispersion of activities) [57] and complex, diverse, but also unique prefabricated elements hamper the assembly accuracy and efficiency. Thus, the onsite assembly has a high requirement for efficient information communication and rapid response to any emergency [58]. Y. Liu et al. [59] pointed out that inefficient supply chain management for the offsite construction system leads to the late delivery of precast elements, project cost and time overruns, and duplicative handling operations, among others. Therefore, effective management of the supply chain is critical to offsite construction success [60]. To realize Construction 4.0, researchers developed various technologies to enable digital manufacturing [61] and construction automation [62] for onsite construction. The technical aspects of these technologies mainly address the collection and exchange of information in real-time for identifying, locating, tracking, optimizing, and monitoring supply chain processes with decentralized control and a high degree of connectivity. They also allow a faster response to customer needs, more flexibility in production systems, and a higher quality of products. In this paper, these technologies were categorized according to the perspective of data into four groups: data acquisition, data integration, data analysis, and decision-making [54].

3.2.1. Data Acquisition

To fulfill the transformation of Construction 4.0, accurate information about the right operation for the right resource at the right time in the right location is essential [63,64]. The collection of this information is the basis for subsequent data integration, analysis, and decision making [65]. Digital technologies can enable the achievement of rapid disturbance response and flexible production configuration and quality control [66] and eventually evolve the production system from automated control to autonomous control [67]. In this paper, data acquisition was divided into three categories based on the way they collect information: document, sensor, and monitor.

Document

Document is a conventional method of data collection with manual input in the form of paper or files. In this review, only one article examined documents in data collection, while it was aimed at presenting the benefits of digital data technologies in a comparative manner. Grenzfurtner et al. [68] and B. Qi et al. [25] pointed out that if data are collected with paper-based tools, they are often only stored in this form or recorded after a certain period of time in some system (e.g., Enterprise resource planning system). In addition, because manual collection occurs during dynamic project execution, information about the actual construction progress is error-prone, incomplete, and not available on time due to errors committed during manual operations [69]. On the contrary, the increased use of digital tools for data has improved data access and timely delivery. By capturing data with digital technologies instantaneously, its availability and accuracy in terms of administration and performance measurement purposes is significantly accelerated (e.g., work hour, production speed, defect detective). This mitigates the risks and potential for data loss inherent in the temporal and spatial separation of construction sites from management locations [68].

Sensor

Sensors can be thought of as devices that sense physical phenomena and generate output signals corresponding to them. They can realize the perception along with real-time data collection and then provide the data for subsequent transmission, processing, decision-making, feedback, and control [70]. They are widely used in offsite construction projects that emphasize indoor positioning accuracy (manufacturing), shipping location accuracy (transportation), and tracking installation progress (assembly), as the primary advantage of sensor technologies is the real-time extraction of information to represent real-time delivery status and material installation status and cases. Many different types of sensors or the integration of these technologies have been implemented in the offsite construction industry. Long-range radio (LoRa) technology is used for data acquisition and transmission to monitor the movement state in the hoisting process [71]. Radio frequency identification (RFID) is used to collect production data from the production floor at every workstation for developing a production planning and control system [72]. Quick response (QR) codes and indoor global positioning systems (GPS) are used to identify individual (prefabricated) elements' geospatial data in order to track prefabricated assets [73–75]. Additionally, laser scanning and photogrammetry [76,77], ultra-wideband [78] and so on are also implemented.

Monitor

Monitor mostly refers to the camera monitoring the dynamic production process of the entire activity, such as taking photos, audio, and video recordings to obtain valuable information from one or more groups of continuous dynamic information to gain data of the real-time movement of tasks. Compared to document and sensor, camera monitoring has the advantages of a noninvasive nature and easier access to comprehensive informative data. It has been applied in the industry for a long time, but its role in gathering information was not obvious from the start due to the inadequate ability to extract and process information. However, with the development of computer vision-based (CVB) technology, camera monitoring has received increasing attention from academics. CVB technology enables a breakthrough in object detection and reliable performance in automatic and real-time job site monitoring [79]. Yan and Zhang [79] used monitors to timely detect related information of task disruptions for evaluating disruption and responding in order to put a disrupted construction project back on track. B. Qi et al. [25] and Ahmadian Fard Fini et al. [80] used monitors to capture images and automatically measure the installation progress in offsite construction with a vision-based recognition system and algorithm. In the near future, computer vision will play a key role in the future development of smart construction and the improvement of quality in construction projects [81].

3.2.2. Data Integration

Within the prefabrication sub-sector, cooperative interaction amongst supply chain allies is a fundamental driver of data integration [82]. However, the continuous flow of data in the project lifecycle is not fully realized, and the barriers in the project lifecycle have not been broken. Two major reasons are: (1) The separation of project stakeholders' tasks in various phases leads to the information island throughout the entire project lifecycle [16]. Data in a prefabricated component supply chain tend to be dispersed in design, production, transportation, and other stages. (2) Interests and security issues are concerned by participants, since they may not come from the same company [83]. To sum up, such data are significantly multi-source heterogeneous [84]. Currently, inadequate information exchange systems are viewed as obstacles to the prefabrication industry, and there is little development and adoption of digital technologies to solve it [85]. Data integration is one of the core concepts of digital twins. This is because the real-time data synchronization and interaction of virtual and physical worlds is the focus of achieving overall analysis and decision making for the entire project. Many cases have proven that project management with integrated data ensures swift and efficient design, fabrication, construction, and assembly processes [86]. In this decade, many studies with digital technologies for data integration were conducted to improve transparency in information sharing. In this paper, data integration is divided into two parts: storage and transmission of data between project stakeholders.

Storage

The database used for data storage can be divided into the self-built database and the cloud-based database by accessible scope. As mentioned in Section 3.2.2 Data Integration, insufficient information exchange among independent project stakeholders hinders the development of the prefabrication industry. Generally, most large businesses are decomposed into independent business units to facilitate agility. Thus, the data production and storage trends are corporate-wide [83], which is called the "self-built database". Data exchange exists only during the task delivery between the databases involved, and this kind of temporal and spatial separation leads to information loss, duplicate work, response delay, and so on. Especially after the advances in automatic data acquisition technologies, a large volume of various data is generated at each phase during the project lifecycle, which is referred to as "Big data" in the manufacturing industry [87]. In this context, various new digital technologies are developed and introduced to build shareable databases to receive Big data. Cloud/web technology is one important method due to its powerful storage and computing power. Doe [88] and L. Wu, Li, et al. [39] utilized cloud-based technology to enable participants to communicate remotely via access to a centrally managed shared database to coordinate data from engineers and suppliers, realizing the integration of the process from design to realization. G. Xu et al. [89] designed a cloud database to store data of all the cloud assets involved in prefabricated construction to improve the involvement and coordination of project stakeholders. Shin and Choi [90] and Wagner et al. [91] also designed a web-based information management system with the MySQL server and algorithm, where different kinds of data generated during manufacturing in a modular factory can be collected and standardized, helping manufacturers break away from the existing document-centered information management.

Transmission

After keeping data from all parties on the same platform, how to ensure data accessibility and timeliness is the focus of data transmission. Having the relevant departments exposed to the production data and giving them the information they need is significant for the efficient and organized operation of the entire supply chain. Additionally, in a dynamic production process, the real-time synchronization of information helps to respond faster to unforeseen situations and allows for better decision-making. The Internet of Things is an advanced digital technology with the ability of enhancing the flow of information along the supply chains of offsite construction businesses. It is a digital interconnected environment that provides seamless integration between logistic processes and the supply chains of offsite construction businesses [92]. G. Xu et al. [89] in 3.1.2 Interoperability section combined IoT with cloud technology to form a service-sharing framework. This compatible and scalable cloud-based IoT platform enables flexible sharing services with different granularities among companies and systems and facilitates their communication and cooperation. Zhao et al. [71] used IoT to achieve the real-time synchronization of BIM models and site sensor information, improving the level of intelligent management of the offsite construction.

Meanwhile, the security and privacy of data also need to be concerned. With these technologies, information exchange between supply chain partners has been made faster and more efficient, but this accessibility under cross-organizational access to the information repository is hazardous. All project information is vulnerable to random or intentional changes by any user [93], which, in turn, detrimentally disrupts trust and market competitiveness among supply chain organizations [85]. Doe [88] used the virtual private network (VPN) to make the could-based database only accessible and modifiable only by insiders. Blockchain is an emerging digital technology designed to improve the traceability, transparency, and security of information exchange between organizations [85]. There are four components that support its operation: distributed database, cryptography, consensus mechanism, and smart contracts [94]. A distributed database is similar to a cloud data center, but the main difference is that it is decentralized, meaning that there are multiple sources/databases of information that can be simultaneously accessible by dissimilar users from dissimilar locations. This distribution ensures that project stakeholders have access to the database regardless of affiliation and location [95]. Cryptography, e.g., hashing algorithms, is applied to encrypt transactions based on a recognized protocol that makes the data difficult to tamper with [96]. The consensus mechanism defines the necessary agreement for maintaining network-wide synchronization [97]. Smart contracts are self-executing contracts that act automatically according to the consensus mechanism when certain triggering circumstances are met [98]. The last three components assist organizations in thwarting malicious attacks on their information repositories through data traceability and user agreement. To sum up, the implementation of blockchain can simultaneously guarantee database accessibility and security in theory, and many cases have shown its greatest potential to deliver business values in construction, which improves information traceability, transparency, security, and sustainability [56,99]. L. Wu, Li, et al. [39] developed blockchain-based supervision on the basis of the digital database to pave the way for a tamper-proof, incentivized supervision mechanism. Z. Wang et al. [100] built a blockchain-based framework to enable the real-time control of information sharing and scheduling among participants from BIM modeling to prefabricated manufacturing.

3.2.3. Data Analysis

There is a huge value hidden in the data. Without systematic analysis, data are just a record, which cannot reflect any situation and provide data support for later decision-making. How to process these data to extract useful information is seen as an important challenge for industry optimization [24]. Data analysis is divided into descriptive analytics, diagnostic analytics, predictive analytics, and prescriptive analytics according to their purposes [101]. With this ordering, the complexity rises, and so does the value it can bring. Among these, prescriptive analytics is the most valuable kind of analysis and usually results in rules about using decision-making tools (e.g., artificial intelligence) to make process optimization. It is the same as the definition of decision-making in Section 3.2.4 below. Thus, in this paper, data analysis was divided into three types: descriptive analytics, diagnostic analytics, and predictive analytics.

Descriptive Analysis

Descriptive analysis is a method used to objectively describe the nature and magnitude of sensory characteristics [102]. It answers the "what happened" by summarizing past data, usually in the form of dashboards. It does not require sophisticated computing power. The digital technology associated with it is primarily visualization because the intuitive representations can improve the speed of overall analysis. The biggest use of descriptive analysis in business is to track key performance indicators (KPIs). KPIs describe performance based on chosen benchmarks. Jiang et al. [56] used the blockchain-based database to prove real-time shareable KPI visualization and evaluation to the blockchain-based database to facilitate cyber-physical construction progress traceability. Zhang, Lei, et al. [103] used integrated value stream mapping (VSM) with a production line breakdown structure (PBS) to analyze current production line performance using key performance indicators (KPIs), to assess the proposed solution for improved performance, and to visualize a construction manufacturing production line.

Diagnostic Analysis

Diagnostic analysis takes the insights found from descriptive analytics and drills down to find the causes of those outcomes. It answers the question of "why did it happen" and provides the right direction to guide the user towards finding a solution. In the offsite construction industry, it is primarily used to discover the causes of various situations in dynamic production processes, providing data support for decision-making. Most of the digital technologies related to diagnostic analysis in these ten years are about mathematical models and algorithms, aiming at obtaining conclusions with computing power. Hsu et al. [104] developed a mathematical model to manage manufacturing and inventory, to determine multiple schedule deviation factors, and finally to react to variations in the demand on the construction site. Meiling et al. [1] validated the viability of the plan-do-check-act (PDCA) method for identifying root causes and thereby reducing deviations in industrialized construction.

Predictive Analysis

Predictive analysis attempts to answer the question "what is likely to happen". This type of analytics utilizes previous data to make predictions about future outcomes. It uses descriptive and diagnostic analytic findings to detect clusters and exceptions and predict future trends, making it a valuable tool for forecasting. Risk assessment, sales forecasting, and user conversion are its main applications. Abdul Nabi and El-adaway [105] used an interrelated multistep research methodology (literature review, online industry survey) with integrated statistical and mathematical digital technologies to predict incurred cost saving and/or growth by incorporating 50 modular associated risks. Tabatabaee et al. [106] developed a prototype risk assessment tool by implementing BIM and analytic network processes for identifying and evaluating the risk factors associated, letting users prioritize the risk factors in offsite construction projects. X. Ding et al. [107] also used statistical and mathematical digital technology to build a grey assessment model of the strategic cost risk of prefabricated buildings to predictively evaluate the return on the investment of offsite construction projects in different regions over different time periods. In terms of user experience, Maslova and Burgess [108] used digital methods of construction to develop a post-occupancy evaluation mechanism, to measure user satisfaction, and to detect defects to use it to improve housing design and construction quality.

3.2.4. Decision Making

Decision making is the last but most important step in project lifecycle management. All previous steps are aimed at providing data to make a better choice. Massive amounts of data generated along with systematic analysis can be used for industry optimization. They can be used to improve offsite construction productivity and operational safety, reduce resource and energy requirements, reduce construction and operational costs, improve payback periods, and enhance sustainability [109]. In this paper, decision-making was divided into manual and automatic decision-making, according to the subject.

Manual

Most of the early decision-makings (2013–2018) were manual, relying on the experience and knowledge of the people involved. In this phase, digital technologies are often used to assist in designing systems. Hedgren and Stehn [110] conducted interviews with key decision-makers to examine the importance of gathering input from client organizations. Arashpour et al. [111] used historical data to perform analytical modeling to define the optimal product sequencing and to evaluate the model's functionality with two offsite manufacturers. Akmam Syed Zakaria et al. [112] used the extensive analysis of literature to inductively classify structural, contextual, and behavioral factors that influence decision-making by offsite construction profession stakeholders aimed at developing a decision frame.

Automation

At a later stage (2018–now), the continuous development of computer-based digital technologies (e.g., artificial intelligence) has led to a shift in the way decisions are made. Actively automated decision-making based on digital technologies gradually replaced the passively manual choices of humans. Hwang et al. [113] conducted a comprehensive literature review and pilot interviews with offsite construction industry experts and built a knowledge base based on artificial intelligence (AI) technology called "expert system" for generating inferences, emulating the decision-making ability of a human expert. Baduge et al. [109] presented a state-of-the-art review of the decision-making-related applications of artificial intelligence (AI), machine learning (ML), and deep learning (DL) in Construction 4.0. ML is another subfield of AI where a computer observes a given set of data and generates a model based on the input data, which can be used to solve problems. DL is a subfield of machine learning, and DL can be understood as the study of artificial neural networks and other related machine learning algorithms. Their contribution to optimizing decision making in architectural, material, and structural design, manufacturing management, and construction management during project lifecycles has been recognized. They also show great potential in life cycle analysis and circular economy with the aim of achieving sustainable development in the industry, which can be seen as "decision making for future".

Meanwhile, robotics is another popular area of automation-related digital technology research used in offsite construction. It highlights emerging hardware developments that illuminate a path toward fully autonomous construction, which is able to operate without supervision or intervention [114]. H. Li et al. [115] designed a robotic car based on the computer vision-based recognition and recognition algorithm to manipulate electric hooks automatically and optimize the hoisting process. In addition, Melenbrink et al. [114] introduced many material-robot systems designed for specific assembly tasks (e.g., Winlet robot for maneuvering and positioning windows and wall panels, Hadrian X for laying concrete masonry unit blocks). Although these robots have some autonomous decision-making capabilities under specific programming, they are not capable of handling unexpected situations outside of their design, often still requiring human supervision. However, it is still a promising area of research with great potential for the realization of Construction 4.0 in the future.

4. Discussion

Applying the criteria of keywords along with publication year and type of source in academic databases, we collected 457 articles. According to the proposed methodology, only papers that conclude the implementation of digital technologies in the offsite construction field were included, selecting 171 articles at last. However, it is worth mentioning that an article may contain multiple application directions under one or more application areas of digital technologies. In order to deal with these cross-area and cross-direction articles in the quantitative analysis, they were counted several times into multiple groups so that the total number of research elements (211 in total) was actually larger than the actual number of articles selected in the quantitative analysis. In addition, the subsection "Multiple" was introduced under each main section to summarize the articles that mention all application directions under that corresponding application area. Except for the five main sections mentioned, there were articles that are general reviews of current implementations of digital technologies in the offsite construction industry or complete management processes of one or more specific offsite construction projects, with many technologies covered in each of the main sections (e.g., case studies). These articles were categorized as "Review" and "Management" respectively. The categorization results are shown in Figure 4.

The descriptive analysis based on the classification of publication categories and years was implemented. Figure 5 shows the descriptive results of publication categories, and Figure 6 shows the distribution of publication frequency by category and year. DfMA was the most popular area this decade. A total of 56 papers (26.5% of the total) were published, followed by data integration with 41 papers (19.4%), review with 33 papers (15.6%), data analysis with 29 papers (13.8%), data acquisition with 22 papers (10.4%), decision making with 17 papers (8.1%), and management with 13 papers (6.2%). It is worth mentioning that, in the DfMA category, the number of publications related to BIM technology reached 62.5%. It is evident that, as a digital technology proposed since 2000, BIM technology is still one of the core technologies in the offsite construction industry and has a high level of attention. Moreover, with the emergence of various computer technologies (IoT, cloud database, etc.), it has also shown good compatibility and operability, appearing in many cross-area/cross direction articles. Many emerging technologies were developed based on BIM technology through various add-ins or algorithms aimed at achieving a digital twin-based Construction 4.0, transforming the BIM model from a one-way guidance for subsequent actual construction to a two-way interactive relationship that can be synchronized with the physical world (supply chain) in real-time and optimized through mutual feedback. In this research direction, interoperability and data integration are also referred to, aiming at expanding its range of applications. Data integration is another very popular research area, because the most important thing to realize in Construction 4.0 is to achieve the integration of design, manufacturing, and assembly (including transportation), the core of which is the integration of data from these three parts. In addition, since the digital twin based on the integration of the virtual and physical worlds emerged from Industry 4.0 and is proven to significantly improve productivity and product quality, there are many technologies and experiences that can be referenced in the offsite construction industry, and their feasibility in this industry is being studied by researchers. During 2013–2016, there were few papers dedicated to data integration in the industry, but then the number of published papers on data integration increased dramatically and ranked second in the total number. The number of review papers related to digital technology implementation in the offsite construction industry was 33. It also increased significantly in these five years, ranking third. This demonstrates the growing interest in the use of digital technology in the field of offsite construction. Ranked fourth, during this decade, the number of papers published on data analysis has undergone a series of fluctuations during this decade. The number of papers published on data acquisition has a similar trend to that on data integration. In the first five years, there were not many papers dedicated to it, but in the last five years, with the rise of the concept of big data, data are becoming more and more important for the analysis and optimization of the industry, and people are paying more attention to data acquisition. At the same time, the development of high performance sensors and computer-vision-based technology has led to a dramatic increase in the number of papers. Except for the management category (13 papers), which describes the overall process for offsite construction projects where three or more application areas are mentioned, the least number of papers was published in the decision making category, with 17 papers. This is one of the most important and complex parts of the process, translating all the previous data preparation into actual optimization operations that bring substantial benefits to the production installation (e.g., increased productivity, reduced costs). Decision-related papers in the first five years focused on empirically based manual decisions, while with the advancement of computing technology, decision-related papers in the second five years were about automatic decision-making based on real-time data and AI-based technology. Making the right decision requires a high level of analysis and judgment ability in the AI system designed, and its feasibility needs to be supported by real-world case studies. This field is still developing; thus, there are not that many papers published.

Figure 7 shows the distribution of publication frequency by year. There is a similar trend in the total number of papers published and in the other six categories, except for data analysis category, in this decade. The number of published papers on digital technologies in the offsite construction industry increased significantly after 2016, and then it stayed constant at about 50 per year during these two years (2021–2022). This reflects the growing emphasis on digital technology among industry practitioners, exploring the feasibility and further benefits that digital technology can bring within the field of offsite construction. Meanwhile, as Construction 4.0 is derived from Industry 4.0, some advanced technologies from the manufacturing industry or other industries, such as IoT, computer vision, and artificial intelligence, have also driven the development of research. The overall research direction can be summarized as follows: to explore the feasibility of the advanced technologies in offsite construction and to modify, improve, and implement them according to the industrial characteristics, eventually realizing the transition from experience-driven manual adjustments to data-driven automation construction.

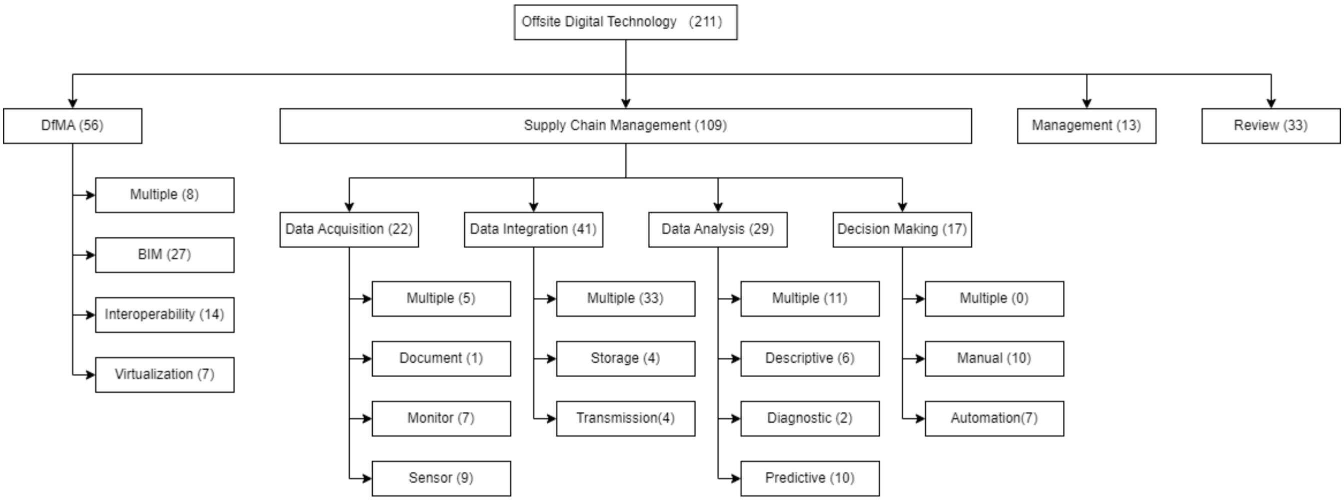

Figure 4. Classification of selected articles.

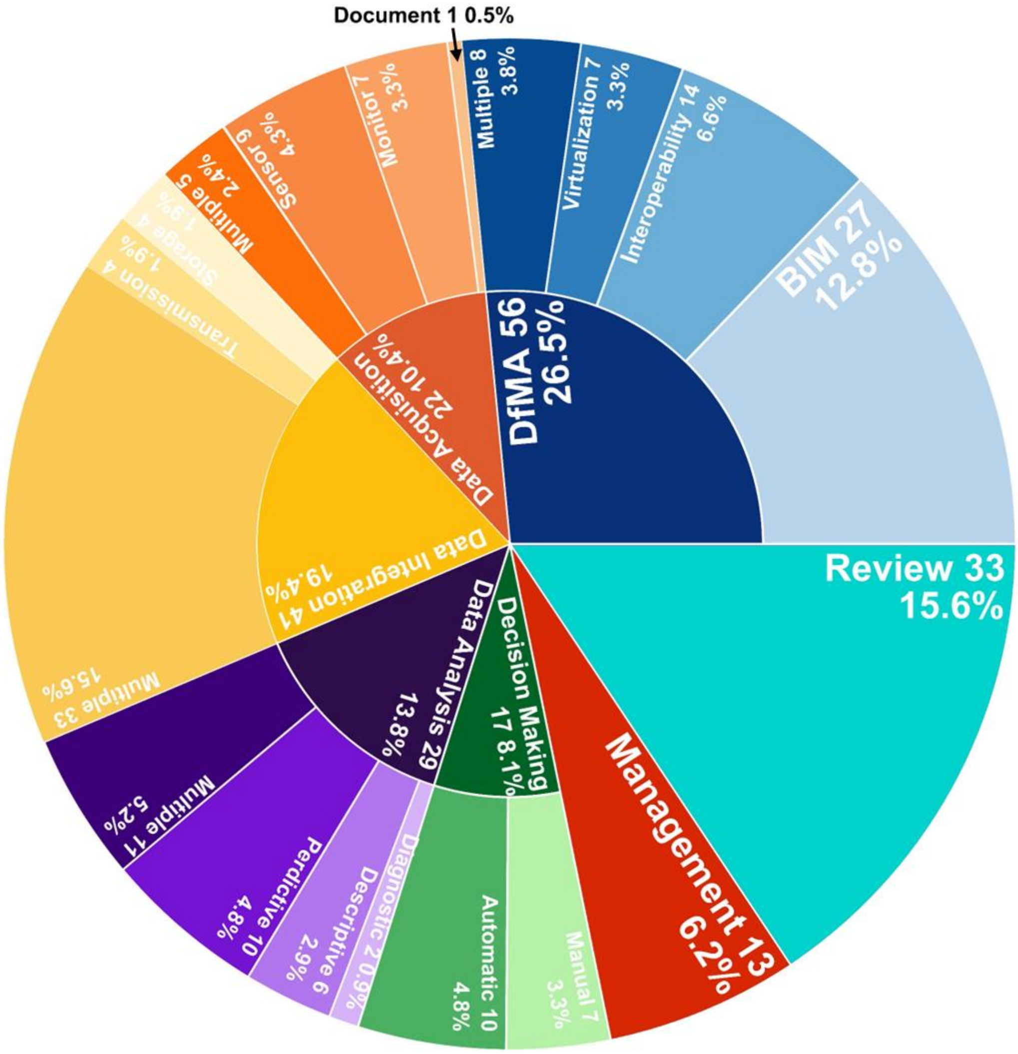

Figure 5. Percentage of publication categories.

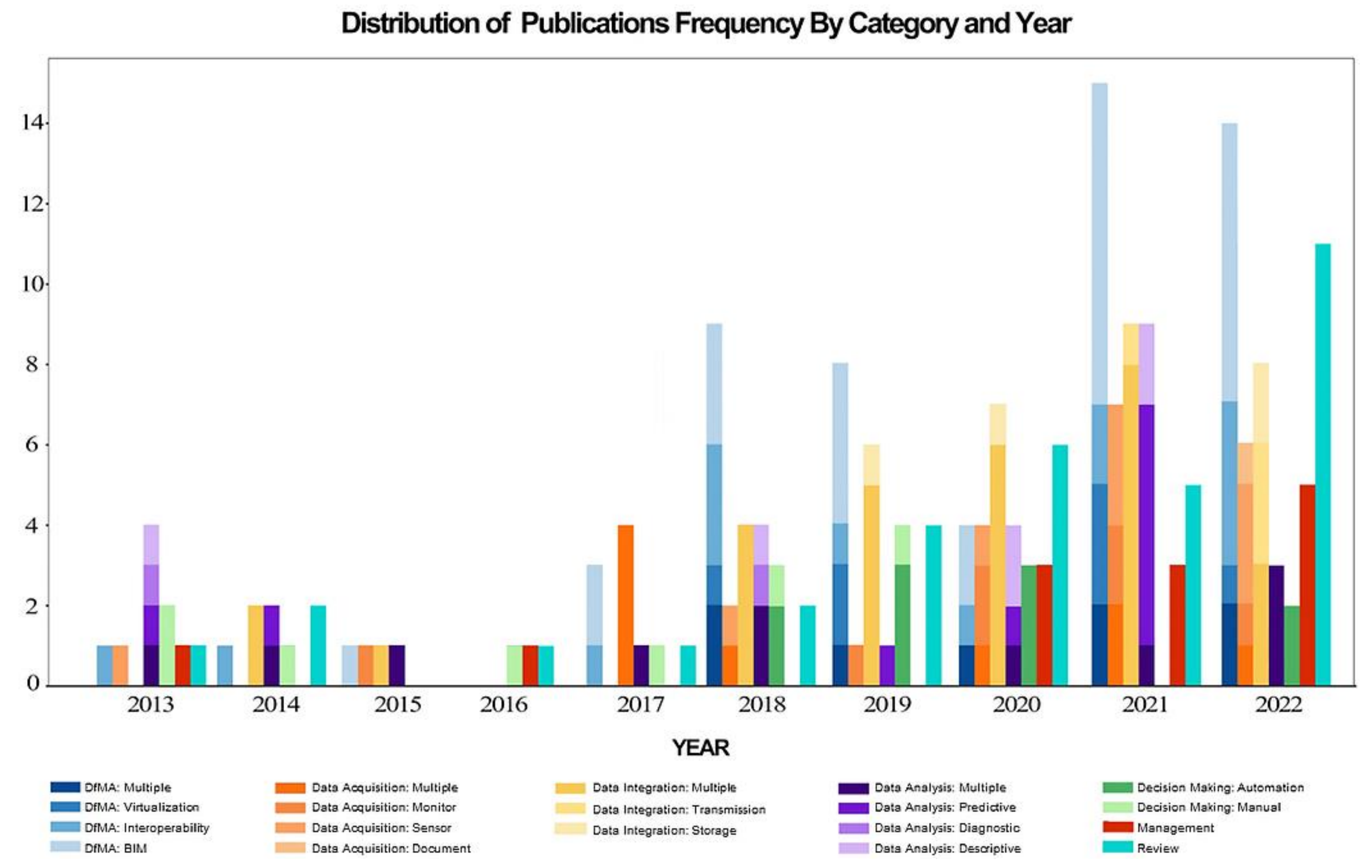

Figure 6. Distribution of publication frequency by category (subcategory) and year.

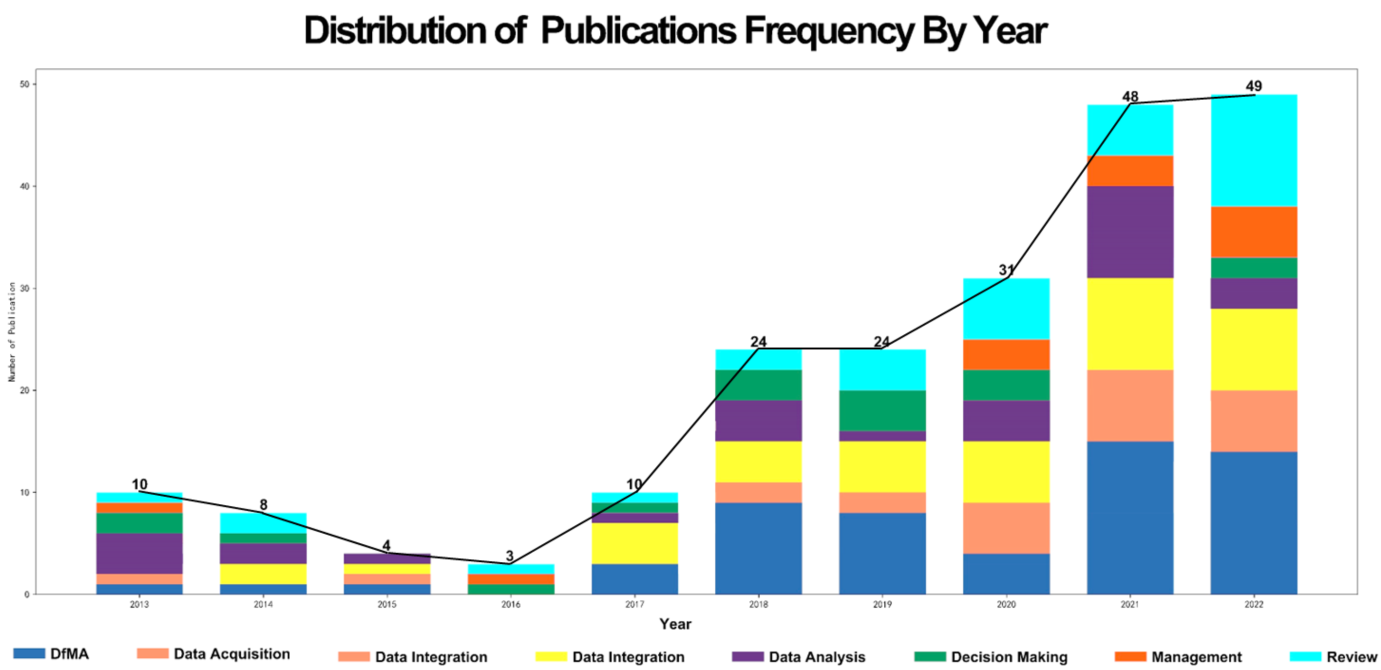

Figure 7. Distribution of publication frequency by year.

However, in the process of stepping into automation, the role of people is rethought as well. Although automation can bring many benefits, AI technology ultimately imitates human behavior, and it has its limitation. The knowledge learned by AI/ML cannot win human domain knowledge. In this context, human–machine interaction is gaining importance, and a concept called "human-in-the-loop" was introduced to tackle the shortages of

AI/ML, which is about incorporating human knowledge into the modeling process [116]. Much research about AI/ML suggests that incorporating user knowledge into the system can be beneficial, and the integration of human domain knowledge is also to promote the automation of AI/ML [117]. Its feasibility in the offsite construction industry was theoretically proven, where seamless human–machine interaction is required for teleoperation in construction workplaces [118]. This will also be one of the future research directions.

5. Conclusions and Future Directions

This research studied the state-of-the-art digital technologies implemented in the offsite construction industry, analyzed the review of literature published in this decade, and provided insights into future research directions. There were 171 articles in the literature review, classified based on the digitalization of construction projects, area of application, and direction of application. Quantitative analyses and introductions were conducted for each category. Future directions can be inferred from the changing trends of research priorities in various fields in recent years. (1) DfMA: Interoperability and integration of BIM and supply chain; BIM technology will still play an irreplaceable role, and the future development of digital technology should be based on the existing BIM technology to expand it. (2) Data acquisition: Automatic real-time extraction of broader and more accurate information; computer vision technology will play a key role in it. (3) Data integration: IoT and cloud-based data transmission; data security and privacy are also increasingly important, and blockchain will be the focus of research in the coming years. (4) Data analysis: Risk assessment related to investment and security. (5) Decision making: AI-based decision-making system and robotics. It is essential for the automation of construction. In general, the entire development trend of digital technology in the offsite construction industry can be concluded as moving from experience-driven manual operations to data-driven automatic operations. However, in the gradual move towards automation in the construction industry, the role played by humans is re-examined, since AI technology currently only imitates human thoughts to make optimization decisions. In response to this challenge, human–machine interaction and "human in the loop" was introduced, which will also be one of the potential focuses of industry development.

This paper is a comprehensive review of articles on digital technologies implemented in the offsite construction industry. It categorized existing technologies based on application areas, described technology features, status, and benefits, and speculated on future research directions. It can help researchers to better understand the technology/technology area, adjust research priorities, and provide guidance for future research directions. Although great efforts have been made, this study has some limitations. First, the classification of the technologies may have some inaccuracy. This is because many papers cover multiple or even all the specific application directions in one or more application areas. It is difficult to disentangle them completely and then categorize them into each specific application area/direction. The "Multiple" subsections under each section, "Management" section, and "Review" section were designed to try to solve this problem by giving these cross-direction or cross-area papers a special classification in the quantitative analysis, but at the same time expand the original grouping (Figure 3) from five groups to seven groups, and they do not solve this problem completely. Second, although this paper adopt3e the review approach that researchers collaborated to filter, group, and verify, the manual categorizing has some inaccuracy due to the different judgment criteria between people. These two factors may contribute to the decline in the number of papers collected in 2015 and 2016 in Figures 6 and 7 in the specific application directions. However, to some degree, the general trend of the research focus in the volume of 171 papers 2qs correct. Moreover, only peer-reviewed articles published in reputable English-language journals in architecture, engineering, management, and manufacturing were considered for this study. Conference proceedings, industry reports, and some interdisciplinary articles were not included. Therefore, some papers with relevant contributions were excluded. Future research should expand the article search scope and collect more high-quality articles to obtain a more accurate industry analysis and future direction speculation by qualitative and quantitative analysis. In addition, future studies should also invite offsite construction industry experts to join the classification to clarify and unify standards and make recommendations for the future direction of the industry from a professional perspective.

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