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Review

Digitalizing Industrialized Construction Projects: Status Quo and Future Development

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Abstract: The construction industry is being profoundly reshaped by the trends of industrialization and digitalization, which, when integrated, offer greater advantages than when applied in isolation. Despite an expanding body of research, a knowledge gap persists regarding the current state and future trajectory of this integration. This study utilizes both quantitative and qualitative review methods to elucidate recent advancements in digital technologies within industrialized construction projects. An analysis of 173 scholarly articles indicates that digital technologies primarily enhance efficiency, flexibility, visualization, and intelligence. The adoption of these technologies varies across different project stages, with a notable trend towards their convergence. However, the operation stage receives significantly less attention compared to the design, production, and construction stages. This study not only identifies specific research gaps for each project stage but also provides recommendations for future research, thereby paving the way for further advancements in the field.

Keywords: construction project; industrialization; digitalization; literature review

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1. Introduction

The global construction industry is undergoing a profound transformation, driven by the dual forces of industrialization and digitalization. By integrating these paradigms, construction projects can achieve higher efficiency and predictability. Industrialization marks a shift from traditional on-site construction methods towards manufacturing and assembly techniques [1]. Prefabrication, a cornerstone of this trend, involves producing building components in controlled factory settings. These components, manufactured with enhanced efficiency and quality assurance, are transported to the construction site for assembly. Panelized and modular construction further expand on this concept, offering extensive design flexibility and construction efficiency. Furthermore, the construction site is progressively adopting advanced machinery to execute component logistics and assembly, thereby addressing challenges such as labor shortages, cost overruns, and environmental concerns [2].

Simultaneously, digital technologies, such as building information modeling (BIM), augmented reality (AR), and the Internet of Things (IoT) are spearheading a digital revolution within the industry. BIM facilitates the creation of detailed 3D models of buildings, serving as central repositories of project information. Beyond visualization, BIM enhances coordination, communication, and collaboration among all project stakeholders [3]. AR provides immersive experiences that improve project visualization and aid in design and construction [4]. IoT devices and sensors are commonly used to monitor and collect real-time data on various project aspects, such as structural health, energy usage, and equipment performance [5]. All these digital technologies play a vital role in automating construction processes, fostering real-time information flows, ensuring end-to-end transparency, and enhancing interactions between workers and machines.

The integration of industrialization and digitalization can maximize the benefits of both paradigms. For instance, Bai et al. [6] demonstrated the integration of digital graphic data from BIM with production information, which ensured a seamless alignment of design details with precast elements. Chen et al. [7] designed a Physical Internet-enabled BIM system to enable the real-time collection, communication, and visualization of information throughout the production, transportation, and on-site assembly processes. Moreover, Bortolini et al. [8] developed logistics planning and control models that can leverage 4D BIM to coordinate the on-site assembly of engineer-to-order components. These emerging research outputs merit a comprehensive summary, which not only assists industrial practitioners in selecting appropriate digital technologies for industrialized construction but also highlights research gaps deserving further exploration.

Earlier investigations have laid the groundwork in this field. Wang et al. [9] provided an overview of different digital technologies used in off-site construction based on a scientometric analysis of 113 journal and conference papers. Li et al. [10] conducted a scientometric analysis of academic papers published from 2009 to 2020 and developed a knowledge map of digital technology adoption in prefabricated construction. Cheng et al. [11] identifies the current stage of applying digital technologies in off-site construction based on 171 journal papers published between 2013 and 2022. Additionally, Zhang et al. [12] summarized the applications of BIM in prefabricated construction based on a review of 103 journal papers. Olawumi et al. [13] reviewed 82 papers on blockchain technology applied to modular construction, while Alsakka et al. [14] examined 24 studies on computer vision applications in off-site construction. However, these review studies generally utilized a single type of review method, focusing on either one type of digital technology or individual stages of industrialized construction.

This study aims to provide a narrative analysis of research on the integration of industrialization and digitalization in the construction industry. It employs both quantitative and qualitative review methods to accomplish three objectives: (1) revisiting the research trend for digital technologies in an industrialized construction setting; (2) synthesizing the roles of digital technologies across the industrialized construction process; and (3) identifying potential directions for future research.

2. Methodology

This study adopts a systematic literature review approach to offer an in-depth examination of the utilization of digital technologies in industrialized construction, as delineated in Figure 1. Initially, the study narrows its focus by outlining the contemporary landscape of digitalization within the field of industrialized construction. This entails a meticulous literature search conducted on the Scopus database, employing a set of predetermined keywords and criteria. Scopus offers extensive journal coverage, a superior quality of citation links, and a more flexible set of filters for literature selection [15]. Specifically, the keywords "digital" AND "off-site construction" OR "prefabrication" OR "precast" OR "industrialized construction" OR "prefabricated construction" are used to retrieve publications spanning from 2014 to 2023. The search string is applied to article title, abstract, and keywords. Additionally, the search is limited to English-language journal and conference articles. Identifying articles from journals and conference proceedings is considered sound practice in systematic reviews, as it ensures a more comprehensive literature sample, mitigates potential publication bias, and captures recent advancements [16].

Following the literature search, a corpus of 298 articles is retrieved. To ensure the integrity of the subsequent analysis, a manual screening process is undertaken to remove irrelevant articles. This screening process targets articles that merely discuss new construction materials (e.g., glass fiber–reinforced polymer reinforcing bars and helically reinforced precast concrete piles), engage in material performance testing (e.g., testing the mechanical properties of materials such as concrete and reinforcing bars), or focus solely on conventional cast-in-place construction methods without direct pertinence to digital technologies in industrialized construction. Furthermore, empirical studies that only refer to the evaluation or application barriers of digital technologies without providing sufficient technical details are excluded during the screening process. Post-screening, a refined pool of 173 literature pieces emerges for systematic analysis. These selected articles are further categorized based on the distinct phases of industrialized construction, including design, production, construction, and operation and maintenance. Within each category, articles are further subdivided according to the specific applications of digital technologies.

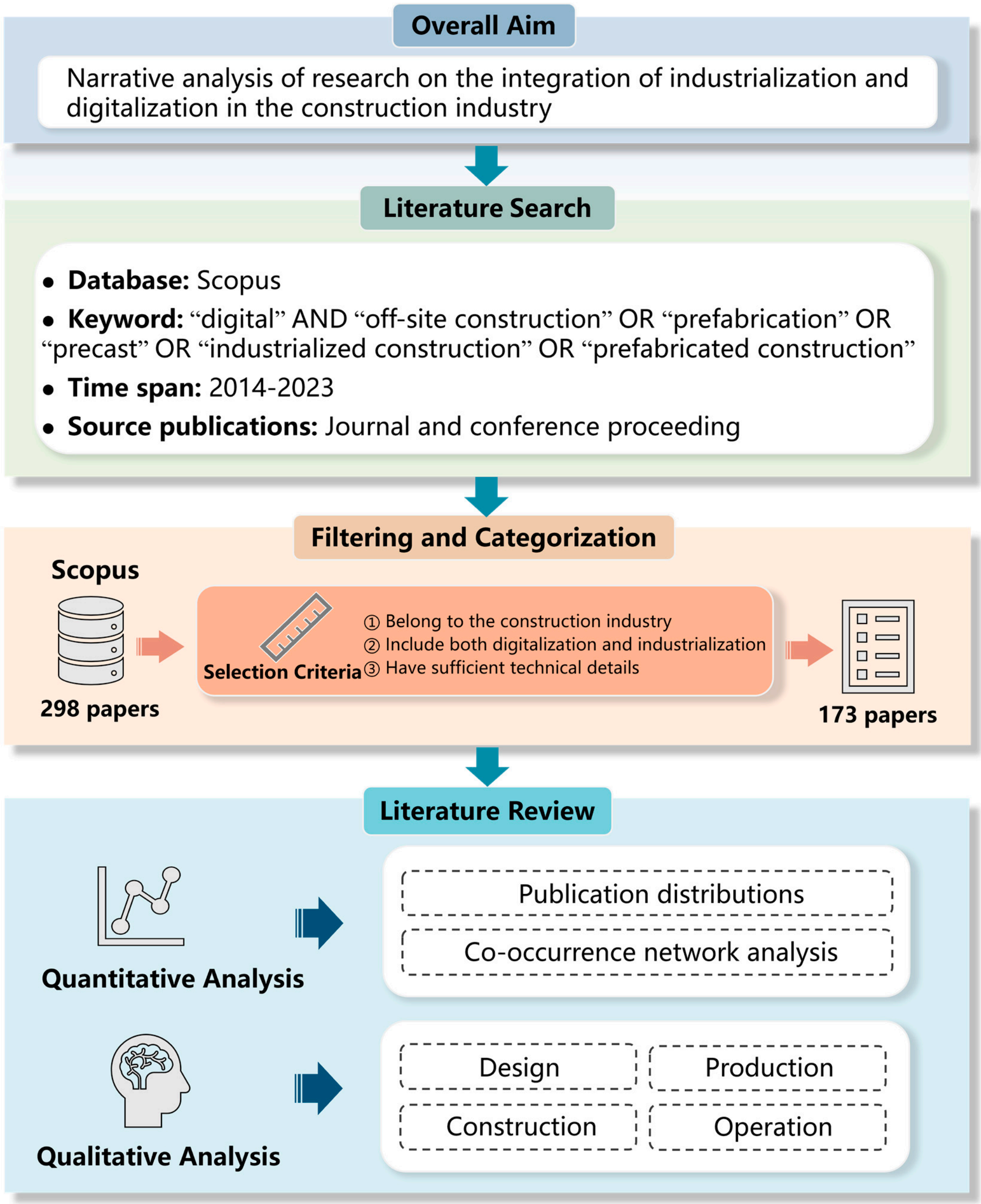

Figure 1. Flowchart of literature review.

By delineating the research problem, adhering to a systematic literature search protocol, and implementing rigorous screening and categorization methodologies, this study ensures the assembly of a representative literature sample. This process, conducted from January to March 2024, is essential for providing a comprehensive appraisal of the latest developments in the field. However, the manual screening process, while necessary to ensure the relevance of the included articles, may introduce a degree of subjectivity and selection bias. To mitigate this, each co-author independently evaluated the articles, followed by discussions to reach a consensus. Furthermore, although the retrieved articles are classified based on the different stages of industrialized construction and targeted applications, providing a structured analytical framework, some articles encompass the applications of digital technologies across multiple stages. This complexity makes it challenging to categorize all articles into specific application areas. To address this, individual articles are classified based on their primary application scenarios.

3. Quantitative Analysis

3.1. Publication Distributions

Figure 2 illustrates the publication trends among the 173 selected articles from 2014 to 2023. During the initial period from 2014 to 2017, the volume of relevant articles remained relatively stable, fluctuating between 6 to 10 publications annually. However, a significant shift in publication dynamics is evident from 2018 onwards, marked by a sustained upward trajectory in the number of articles. This trend culminates in 2021, with the annual publication count reaching 32 articles.

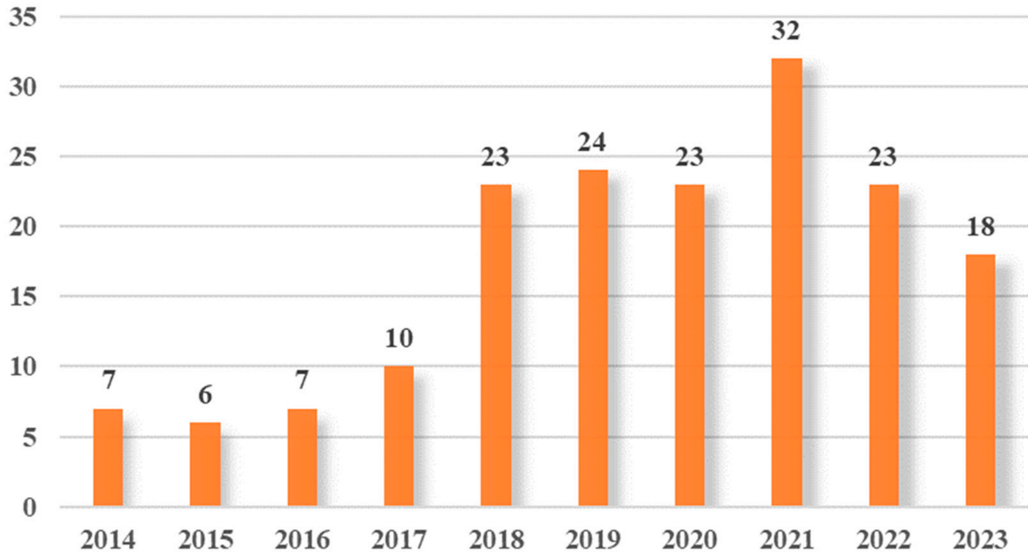

Figure 2. The publication year of the selected articles.

The observed surge in research output underscores a heightened interest and concerted scholarly engagement with the subject matter. Consequently, the subsequent phase of this review will focus on investigating the research hotspots and pivotal advancements that have emerged since 2018.

3.2. Keyword Co-Occurrence Network Analysis

To elucidate the principal research trajectories and thematic concentrations concerning the applications of digital technologies in industrialized construction, we employed VOSviewer software 1.6.19 to construct a comprehensive keyword co-occurrence network. Within the corpus of the 173 selected articles, we utilized both "author keywords" and "indexed keywords" derived from article titles and abstracts sourced from the Scopus database. To enhance semantic clarity and analytical precision, lexically synonymous keywords were harmonized, as delineated in Table 1. For instance, terms such as "additive manufacturing" and "concrete printing" were amalgamated under the consolidated rubric of "3D printing". Moreover, generalist keywords such as "concrete", "building", and "facades" were judiciously excluded. While these terms are undoubtedly relevant to the broader context of construction, they do not directly contribute to the understanding of how digital technologies are being applied and developed in industrialized construction. Conversely, keywords such as "industrialized construction", "off-site construction", and "precast elements" were retained due to their direct alignment with the research objectives. Through this meticulous curation process, a total of 47 distinct keywords were curated for analysis. Figure 3 illustrates the keyword network, wherein each node corresponds to a unique keyword, with the magnitude of the node size denoting its frequency of occurrence across the ensemble of selected articles. The interconnecting lines between nodes delineate co-occurrence relationships among keywords, with the thickness of each line indicative of the robustness of the respective association, while the spatial separation between nodes signifies their semantic correlation.

Table 1. Normalized keywords list.

No.	Original Keywords	Normalized Keywords
1 2	additive manufacturing concrete printings	3D printing
3 4 5	3d printers laser scans laser scanning	3D laser scanning
6 7	building information modeling building information modelling (bim)	BIM
8	block-chain	blockchain
9 10	computer aided design computational design	CAD
11 12	computer numerical control machines computer control systems	computer numerical control
13	digital twins	digital twin
14	data storage equipment	digital storage
15	design for manufacture and assemblies	DfMA
16	information interoperability	interoperability
17 18	digital fabrication with concrete digital manufacturing	digital fabrication
19 20	iot internet of things (iot)	Internet of Things
21	industrialized building	industrialized construction
22	life cycle analysis	life cycle assessment
23 24	modular construction modular integrated construction (mic)	MiC
25	offsite construction	off-site construction
26	timber prefabrication	prefab timber
27 28	precast concrete elements prefabricated components	precast elements
29	robotic fabrication	industrial robots
30	radio frequency identification technology	RFID
31	risk analysis	risk management
32	discrete event simulation	simulation

Detailed quantitative insights are presented in Table 2, where the total link strength metric indicates the extent to which a keyword is connected to others in the network, revealing the centrality and influence of certain technologies or concepts within the research landscape. For instance, the high total link strength of "BIM" and "industrial robots" suggests these technologies are strongly associated with various aspects of industrialized construction and are likely key enablers of digital transformation in this field. The occurrences metric highlights the popularity and prevalence of specific research topics, with higher occurrences indicating greater scholarly attention and potential impact. The top five most frequently occurring keywords are "BIM", "precast elements", "life cycle assessment", "information management", and "digital storage". The predominance of "BIM" within the keyword network underscores its pivotal role as a linchpin technology in industrialized construction. Its multifaceted functionalities, including information management and digital storage, constitute foundational pillars underpinning the realization of digital collaboration and information integration within industrialized construction workflows. Meanwhile, the prominence of "precast elements" reflects the increasing use of precast elements, which relies heavily on digital technologies for standardized and modular design, manufacturing, and assembly. The frequent appearance of "life cycle assessment" suggests a growing emphasis on sustainability considerations, with digital tools being leveraged to optimize building performance and minimize environmental impact. Collectively, these keyword connections depict an industrialized construction sector harnessing digital technologies to streamline conventional construction processes, enhance information collaboration, and improve overall project effectiveness. Furthermore, the Avg. Pub. Year metric provides valuable insights into the temporal evolution of research interests, enabling the identification of emerging trends in recent years. For instance, the relatively recent average publication year of keywords such as "digital twin", "structural health monitoring", "augmented reality", "blockchain", and "machine learning" indicates that these technologies are gradually gaining prominence in industrialized construction. The emergence of these technologies suggests a continuous exploration of avenues toward virtual–reality integration, human–machine interaction, building structural monitoring, information security and transparency, and intelligent decision-making within the field.

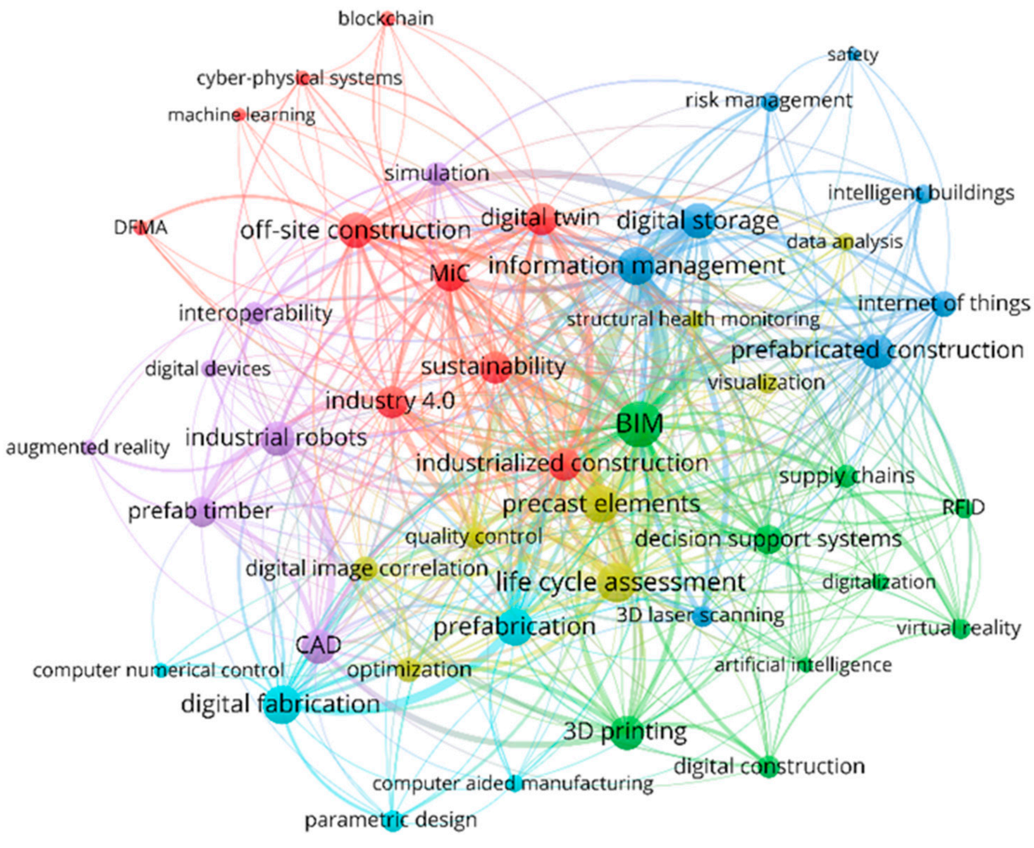

Figure 3. Keyword co-occurrence network.

Table 2. Quantitative measurements of journals' influence.

Label	Total Link Strength	Occurrences	Avg. Pub. Year
BIM	188	45	2019.87
precast elements	123	27	2018.95
life cycle assessment	111	30	2020.63
information management	100	27	2019.33
digital storage	95	24	2018.63
industrialized construction	79	19	2020.29
off-site construction	79	24	2020.83
digital twin	77	19	2021.63
sustainability	76	18	2020.19
MiC	74	18	2020.39
industry 4.0	72	19	2020.47
industrial robots	69	22	2018.92
3D printing	62	22	2020.00
CAD	62	22	2018.86
decision support systems	61	14	2020.21
quality control	61	7	2019.00
internet of things	48	11	2019.09
prefab timber	44	16	2019.75
3D laser scanning	32	7	2017.14
interoperability	31	8	2019.63
supply chains	28	8	2019.88
virtual reality	24	6	2020.00
artificial intelligence	22	3	2020.00
RFID	21	5	2019.60
risk management	18	5	2019.60
visualization	17	6	2019.17
parametric design	16	7	2018.14
computer aided manufacturing	15	4	2019.50
structural health monitoring	13	4	2021.25
augmented reality	8	3	2021.00
blockchain	8	3	2022.33
computer numerical control	8	3	2019.33
DFMA	8	3	2021.00
machine learning	7	2	2021.00

4. Qualitative Analysis

The expanding body of scholarly literature addressing the digitalization of industrialized construction offers crucial insights into multifaceted focal points. Illustrated in Figure 4, an analysis of the 173 articles reveals a nuanced categorization based on their targeted applications, delineating four principal phases: (1) the design phase, encompassing parametric and discrete design methodologies, design tailored for manufacturing and assembly, and performance assessment (Section 4.1); (2) the production phase, which involves digital manufacturing techniques, process optimization strategies, and the implementation of quality inspection protocols (Section 4.2); (3) the construction phase, incorporating facets such as information communication and exchange, construction scheme planning, logistics management mechanisms, real-time safe monitoring frameworks, and the integration of automated assembly procedures (Section 4.3); and (4) the operation and maintenance phase, featuring predictive maintenance protocols and sustainable operation practices (Section 4.4).

4.1. Design Phase

4.1.1. Parametric and Discrete Design

Parametric design, leveraging advanced computational tools and algorithms, facilitates the generation of building geometries based on predefined parameters such as dimensions, materials, and form. This approach empowers designers with the flexibility to explore intricate geometries and unconventional forms efficiently [17]. For instance, Jo et al. [18] demonstrated a unique marina featuring tulip-shaped concrete 'pots' with undulating profiles, necessitating parametric modeling to consider prefabrication, structural integrity, and aesthetic considerations simultaneously. The essence of parametric design lies in its capacity to translate design variables into parameters, thereby enabling the rapid creation of diverse design solutions. The integration of performance-driven optimization with parametric design can support iterative refinement under the influence of performance and manufacturing considerations [19].

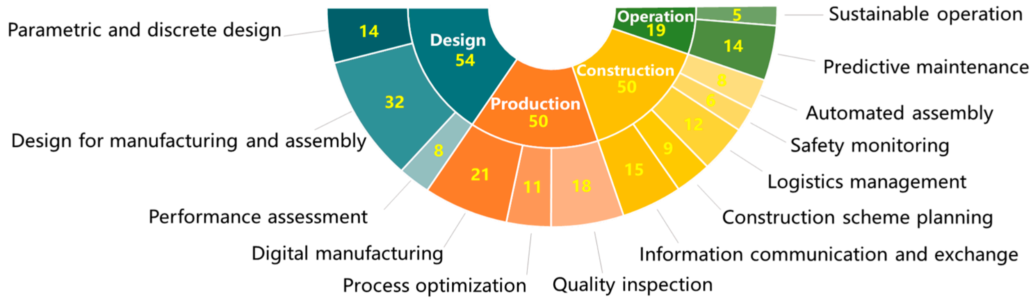

Figure 4. Categorization and number of selected articles.

Discrete design, emerging as a distinct approach, departs from traditional top-down processes by starting from the design of generic units and exploring their combination logic. Situated between fully programmable matter and standardized modular prefabrication, discrete building blocks offer a level of flexibility and configurability. For example, Colella [20] presented a prototype of a truncated icosahedral-shaped dome house composed of interlocking pentagonal and hexagonal structural lightweight timber modules. This geometric flexibility allows designers to craft visually unified design outputs. Retsin [21] utilized discrete techniques to cut and fold wood panel materials into larger elements, enhancing efficiency and architectural novelty. Additionally, Boyd et al. [22] introduced a digital discretization process for complex geometries, enabling the customization of fully composite structural shell assemblies based on various design, geometric, and engineering parameters.

Despite the evolution of parametric design driven by the quest for nonlinear design solutions, the design of free-form surfaces remains inherently linked to discretization techniques. Parametric design enhances the adaptability of discrete design by adjusting parameter values to control the morphology and arrangement of discrete modules. For instance, Tošić et al. [23] combined discrete differential geometry with the response surface methodology to perform the multi-objective optimization of globally parameterized shapes, exemplifying how parametric design can improve discrete design under specified constraints. However, the practical realization of these shell structures in actual construction projects remains pending.

4.1.2. Design for Manufacturing and Assembly

Design for Manufacturing and Assembly (DfMA) represents a strategic approach aimed at optimizing design by integrating manufacturing and assembly constraints, with the overarching goals of cost reduction and producibility enhancement [24]. This approach encompasses two primary aspects: Design for Manufacturing (DfM) and Design for Assembly (DfA).

DfM considers manufacturing process constraints and operational capabilities to ensure that building components harness manufacturing capabilities to their fullest potential without surpassing them [25]. For instance, Zazire et al. [26] utilized genetic algorithms to refine the initial shape of an arch structure, thereby augmenting the efficiency of robot-assisted manufacturing. Through DfM, products are engineered to fulfill functional requirements while effectively managing production time, cost, and quality within acceptable thresholds. Rausch et al. [27] developed optimization algorithms for panel unfolding and nesting, refining panel geometry and topology to optimize material utilization. Retsin et al. [28] developed local optimization models for large-scale 3D-printed concrete structures, which mitigate computational complexity and provide efficient design support for the flexible production of intricate structures. Additionally, Monizza et al. [17] facilitated the mass customization of precast elements, such as glued laminated timber, through optimization algorithms, in order to achieve both material utilization efficiency and manufacturing flexibility.

The absence of comprehensive knowledge pertaining to manufacturing and assembly details can lead to a disconnect between design intent and production. Digital modeling addresses this issue by bridging the design and manufacturing phases. For example, Collins et al. [29] linked data from digital models representing both global (layout of panel boundaries) and local descriptions (detailed component pieces) of architectural precast components, thus bridging the workflows and values of designers and fabricators. The integration of BIM into design and fabrication workflows holds the potential to bolster productivity. For instance, Collins [30] incorporated manufacturing details into the design model of precast concrete components, including methods for generating digital models, producing shop drawings and shop tickets, and creating custom models. Furthermore, Pupeikis et al. [31] demonstrated the use of digital production workflows and open BIM standards, such as IFC, to automate data flow in rebar fabrication. Kaiser et al. [32] further automated simulation model generation for reconfigurable manufacturing systems for wood structures. However, current IFC standards exhibit limited support for prefabrication [33].

DfA focuses on enhancing the constructability and predictability of component assembly through design strategies [34]. For instance, Cuellar et al. [35] proposed a design approach to optimize drywall installation layouts. This approach achieved improvements of 37.5%, 7%, and 54% for environmental, cost, and aesthetic factors, respectively. Mohamed et al. detailed the design and production of system components using BIM modeling and structural analysis, thereby supporting predefined assembly at the job site [36]. Nonetheless, on-site construction introduces uncertainties, and precast elements may deviate due to quality variations. To bolster the predictability of element installation, Murphy et al. [37] employed virtual design and construction methods to develop highly detailed fabrication models. These digital methods enhance predictability regarding site conditions and facilitate early consideration of installation variances during the design phase, aligning seamlessly with the objectives of DfA.

4.1.3. Performance Assessment

Performance assessment plays a crucial role in improving a project's performance and mitigating environmental impact over its entire life cycle. By analyzing various facets such as energy consumption and carbon emission, designers can refine building schemes early on. For instance, Yu et al. [38] simulated the internal surface temperature and heat release of a wall throughout the year, thereby determining the optimal phase-change material and thickness for energy-efficient precast concrete walls. Similarly, Debnath et al. [39] compared the environmental performance of timber and concrete structures by using a multizonal energy simulation, which elucidated the superior energy efficiency and thermal comfort of timber structures. Furthermore, Sousa et al. [40] proposed a robotic fabrication-based material system that combined the sustainability properties of cork with the structural efficiency of concrete. The harmonious integration of these materials provides an environmentally friendly solution.

Life cycle assessment (LCA) is a valuable tool for assessing a building's environmental impacts from raw material extraction to disposal. The integration of LCA into the building design process offers substantial potential for minimizing environmental impacts. For instance, Ansah et al. [41] introduced an automated process to merge comprehensive and detailed LCA data into BIM models, evaluating buildings' environmental performances through systematic zoning, model setup, and impact estimation. Manca et al. [42] also developed a BIM-based LCA methodology and used environmental impact data to assess, optimize, and compare various design alternatives. These methods streamline the data-intensive LCA process and increase designers' willingness to apply LCA in the design phase of industrialized construction. However, their effectiveness is limited by the paucity of accurate environmental impact data.

In summary, the existing research on the design phase of industrialized construction highlights several key areas. First, parametric design enables the efficient exploration of complex geometries and forms by defining parameters such as size, material, and shape. Discrete design leverages generic components to explore the flexibility of component combinations, while maintaining a visually cohesive design. Second, DfMA aims to optimize designs to reduce costs and improve producibility by considering manufacturing and assembly constraints early in the process. Performance assessment evaluates energy use and emissions to refine the design and mitigate environmental impacts throughout the building lifecycle. Third, BIM bridges the gap between design and production by incorporating manufacturing details into the digital model. However, limitations persist in terms of data availability and support for prefabrication standards.

4.2. Production Phase

4.2.1. Digital Manufacturing

Digital manufacturing encompasses the utilization of digital tools such as 3D printing and Computerized Numerical Control (CNC) to enhance productivity, reduce material waste, and improve the customizability in precast element production. This advancement enables the production of more complex, high-performing, and sustainable precast elements with greater accuracy.

Three-dimensional printing technology demonstrates remarkable potential in digital manufacturing, particularly in dry assembly, implementation speed, and recyclability. Volpe et al. [43] employed extrusion-based 3D concrete printing technology to fabricate building envelope components. Despite the geometric flexibility afforded by 3D printing in crafting non-standard components, concerns persist regarding geometric accuracy. Therefore, Meibodi et al. [44] illustrated how robotic fused deposition modeling can efficiently fabricate large, lightweight, ready-to-pour freeform formwork for non-standard concrete components. Moreover, Anton et al. [45] proposed an automated 3D concrete printing platform tailored for fabricating custom columns with intricate geometries and textures, highlighting its advantages in bolstering constructability.

Regarding sustainability, Asensio et al. [46] quantified the environmental impact of 3D printing technology and identified that, while 3D printing generates fewer greenhouse gas emissions than conventional solutions, there is still room for improvement in economic indicators for competitive solutions. Placzek et al. [47] integrated 3D printing with lean manufacturing techniques, prioritizing on-demand production and bi-directional digital workflows to reduce material waste. Fardhosseini et al. [48] explored the cost-effectiveness of using CNC machines for concrete formwork, and concluded that CNC machines can amplify labor productivity, manufacturing quality, and worker safety. Meibodi et al. [49] pioneered lightweight concrete floor slabs through hybrid 3D-printed and CNC-manufactured formwork, achieving a 70% weight reduction. This quantitatively illustrates how digital manufacturing can facilitate the development of more sustainable structures.

4.2.2. Process Optimization

The need for production process optimization arises from factors like uncertainty, multiple projects, and variable production requirements. Process optimization leverages digital technologies such as digital twins, human–machine collaboration, and other digital tools to enhance production flexibility and address challenges posed by fluctuating demand. Fardhosseini et al. [50] devised automated procedures utilizing digital modeling and CNC machines to support a comprehensive design-to-fabrication workflow. This holistic approach to process optimization has yielded gains in both efficiency and manufacturing quality. Barkokebas et al. [51] introduced a digital twin system in the shop that automates the reassignment of multi-skilled workers based on real-time production data updates, thereby enhancing production flexibility. This data-driven dynamic scheduling approach shows considerable benefits in complex production environments.

Human–machine collaboration enhances productivity and flexibility in industrialized construction. Wolf et al. [52] proposed a data model for the continuous description of building components, which enables a generic description of tasks, operations, and manufacturing environments. Kyjanek et al. [53] introduced an interactive manufacturing process wherein workers used AR head-mounted displays to plan production sequences. Additionally, Amtsberg et al. [54] exemplified human–robot collaboration through AR in timber frame assembly. In this scenario, four humans and a seven-axis robotic system receive task assignments based on their respective skill sets. This collaboration harnesses the flexibility of humans along with the high precision of robots, thereby improving the overall performance of the production process.

4.2.3. Quality Inspection

Quality inspection entails the application of digital technologies such as 3D laser scanning and BIM to evaluate the geometric dimensions, surface quality, and other quality parameters of precast elements during the production process. This ensures the timely correction of quality issues to meet design specifications.

The increased utilization of precast concrete elements (PCEs) in industrialized construction necessitates meticulous inspections to ensure compliance with specified tolerances, but manual inspection often leads to the delayed detection of geometric errors, due to a lack of systematic data storage and transmission mechanisms. To address this, Kim et al. [55] presented an end-to-end framework for PCE dimensional and surface quality assessment, incorporating inspection checklists, procedures, scanner selection, and data storage methods. Kim et al. [56] proposed a dimensional quality assessment system leveraging 3D laser scanning and BIM, catering to the growing demand for dimensional quality control. Similarly, Kim et al. [57] introduced a laser scanning-based dimensional quality assurance technique that can achieve a measurement accuracy of 3 mm. Additionally, Liu et al. [58] proposed the use of a Terrestrial Laser Scanner to concurrently scan multiple PCEs, convert 3D point cloud data to 2D images, and adopt the Rotated Binary Neural Network algorithm to achieve automatic segmentation from the as-designed BIM model. This approach streamlines the extraction of diverse PCE types from extensive laser scanning data, thereby enhancing inspection efficiency.

The current state of research on the production phase of industrialized construction encompasses several key areas. First, digital manufacturing employs tools such as 3D printing and CNC to enhance the customization, sustainability, and productivity of precast elements, despite ongoing concerns about the accuracy of some techniques. Second, process optimization strategies enhance flexibility in response to varying demands, resulting in improvements in efficiency and quality. Third, quality inspection methods that integrate laser scanning and BIM support dimensional compliance checking, though further advancements in practicability are necessary.

4.3. Construction Phase

4.3.1. Information Communication and Exchange

Information communication and exchange harnesses digital technologies to proficiently manage information generated throughout the construction process, so as to improve the visibility, transparency, and collaborative efficiency of the entire construction phase. Central to this is standardization. For instance, Lou et al. [59] introduced a naming system tailored for standardizing the nomenclature of prefabrication components. This standardization lays a foundational framework for efficient coordination in the digital era. Dong et al. [60] developed a construction management information model to ensure interoperability in graphical databases.

A primary challenge in information transmission revolves around inefficient transfer and potential data loss. Lei et al. [61] documented wood panelized construction processes and the associated information requirements for digital design tools and automated machinery. Their proposed generic simulation-based approach can measure the impacts of information transfer and data loss during construction processes. To mitigate data loss due to poor data interoperability, Daniotti et al. [62] developed a BIM management system for different stakeholders that can be accessed by designers, contractors, and occupants. Such a system provides a standard framework for information exchange, as well as the integration of relevant data such as building energy performance, building acoustics, and occupant behavior. Zhai et al. [63] designed an IoT-enabled BIM platform that linked component information throughout the stages of production, transportation, and on-site assembly. Jiang et al. [64] developed a blockchain-based digital twin platform that realized information exchange across the business, technical, and management domains.

Furthermore, studies have also endeavored to fortify data accuracy and security. Ding et al. [65] combined BIM and reverse engineering to accurately communicate building geometry information and rapidly reconstruct 3D digital models. Li et al. [66] proposed a two-tier adaptive blockchain model tailored for supervising off-site modular housing production. This model struck a balance between storage costs and privacy protection. These collective efforts contribute to the advancement of information communication and exchange practices in industrialized construction.

4.3.2. Construction Scheme Planning

Construction scheme planning involves the adept use of computer-aided tools, virtual reality (VR), and other digital technologies to meticulously strategize project delivery. This process entails detailed schedule estimation, risk assessment, performance tracking, and disruption detection. All aim at achieving the visualization, simulation, and optimization of the construction program.

In developing the construction schedule, numerous influencing factors must be considered. This can be achieved through employing VR and 4D BIM [67]. Correa [68] introduced a framework integrating BIM, sensors, and machine learning to streamline construction scheduling. Marcinkowski et al. [69] further devised an interactive computer-aided assembly planning method grounded in a Monte Carlo simulation and logical algorithms. This method accounted for variables such as the number and type of fixed/mobile cranes and their potential locations, ranking each simulation result based on criteria including assembly operation cost, assembly time, and the number of precast elements not yet mounted.

To consider construction schedule risks, Li et al. [70] developed a hybrid dynamic model to assess the dynamic impact of the interrelationships of various risk variables on assembly performance. The model reflects the actual project schedule and performs risk analyses for factors such as the inefficient verification of precast elements due to unclear labeling, misplacement due to carelessness, owner crane failure and maintenance, etc.

To ensure a smooth project delivery, ongoing construction program planning remains imperative even after construction has begun. A digital twin applied to the planning, scheduling, and execution of component assembly can realize real-time monitoring and dynamic control, forming a two-way virtual–physical interaction [71]. Additionally. Ahmadian et al. [72] employed image processing algorithms, in combination with time-lapse photogrammetry, to achieve the on-site installation progress measurement of prefabricated wood buildings. Yan et al. [73] also used computer vision methods to detect real-time construction site disruptions. To sum up, computer vision techniques provide more accurate construction progress monitoring, while digital twin techniques focus on overall construction progress planning and control.

4.3.3. Logistics Management

Logistics management involves adept planning, coordination, and optimization within supply chain and logistics management contexts. This is achieved through the utilization of integer programming models, optimization algorithms, BIM, VR, and simulation techniques. The primary aim is to ensure the seamless operation of the logistics chain and optimal resource utilization.

Mathematical models have been used to reduce logistic costs within industrialized construction settings. Wang et al. [74] developed an integer programming model to minimize total logistic costs, encompassing trailer rental, fuel consumption, and labor expenditures. Almashaqbeh et al. [75] introduced an optimization model focused on minimizing both the transport and on-site storage costs of prefabricated modules. It is noteworthy that the effectiveness of the model is most pronounced in the transport of rectangular modules and may exhibit diminished efficacy for irregularly shaped counterparts.

The assessment of logistic costs should extend beyond direct economic outlays to consider external costs, including environmental burdens not directly borne by the involved parties. These external costs may encompass greenhouse gas emissions, air pollution, and traffic congestion, among others. However, the accurate estimation of external costs necessitates comprehensive and precise data, such as vehicle or tonne-kilometer metrics. Consequently, Brusselaers et al. [76] devised an integrated impact assessment framework for construction logistics flows, facilitating the evaluation of economic and environmental impacts associated with various logistics solutions.

Conceptual models and VR systems also play pivotal roles in enhancing component logistic planning and inventory management. Si et al. [77] proposed a conceptual model that integrated an information-sharing platform, dynamic resource management, and optimization system to ensure on-time coordination among stakeholders. In a similar vein, O'Grady et al. [78] utilized VR simulation in conjunction with BIM to visualize material flows and inventories, thereby facilitating the identification of materials and components suitable for reintegration into the supply chain at the end of their useful life.

Furthermore, discrete event simulation can be employed for impact assessments and strategic decision-making in sustainable supply chain management. Chen et al. [79] compared construction durations, costs, and greenhouse gas emission metrics under different supply chain strategies, based on the varying production and delivery capabilities of component suppliers. Meanwhile, Liang et al. [80] developed an intuitionistic fuzzy large group decision-making model for selecting component suppliers. This model considers criterion weights, decision maker weights, and the inherent fuzziness in decision-making, thereby addressing diverse needs for selecting appropriate suppliers.

4.3.4. Safety Monitoring

Safety management during construction, particularly in critical tasks like lifting and assembling, is paramount for ensuring on-site safety. The integration of the IoT, BIM, digital twins, and other advanced technologies facilitates the perception, analysis, and prediction of potential safety hazards. This integration enables the timely detection of and response to safety threats. The IoT acts as the "keen eye" of safety monitoring. Radio frequency identification (RFID) combined with GPS can collect real-time data on the type, production attributes, arrival time, location, and installation status of precast elements. The data is uploaded to the cloud, providing decision support for site management personnel and workers [81]. However, RFID may encounter issues such as limited coverage and unstable information transmission on construction sites. In contrast, low power consumption data transmission (LoRa) and a narrowband Internet of Things (NB-IoT) can offer better coverage and reliable data transmission [82].

The analysis of on-site data is important for safety risk assessment and dynamic safety control. Nevertheless, many risk analysis methods overlook the interaction of risk factors. To address this gap, Liu et al. [83] introduced a digital twin-based lifting risk management framework that incorporates a risk-coupling model. This model enables real-time sensing and the virtual–real interaction of multi-source data, such as safety protection wearing status, sling inclination, the quality level of precast elements, the actual service life of hoisting machinery, and the layout of the storage yard. Furthermore, Liu et al. [84] proposed a safety risk prediction framework leveraging a digital twin–support vector machine algorithm to forecast lifting risks in advance.

4.3.5. Automated Assembly

Automated assembly, facilitated by an array of digital technologies, including RFID, BIM, AR, digital twins, and robotics, aims to enhance the installation of precast elements, foster intelligent assembly through human–machine collaboration, and enable customized automated assembly processes. By harnessing these technologies, the industrialized construction process can reduce manual operation errors and achieve higher efficiency.

One strand of research centers on various tools to augment the productivity of field workers. This requires dynamically adapting the operational strategy to current information and updates in environmental conditions. Charnwasununth et al. [85] introduced a dynamic information support system that utilizes RFID to identify available resources and a multi-agent system to collect actual conditions, generate alternatives, and provide dynamic information appropriate for the assembly sequence. Amtsberg et al. [86] proposed an AR interface to coordinate human artisans with robotic manufacturing cells, thereby streamlining prefabricated timber assembly. Additionally, Podder et al. [87] used digital twins and VR to enhance assembly training and working practices in automated building environments.

Another avenue of research focuses on modular assembly employing industrial robots. For instance, Ron et al. [88] outlined the on-site robotic assembly of desert habitat structures, laying the groundwork for the robotic assembly of custom modular buildings. Complementarily, Ariza et al. [89] proposed an approach linking robotic assembly with the in situ 3D printing of custom connections for building components. Furthermore, Iturralde et al. [90] integrated digital fabrication and robotic assembly to automate the assembly of semi-custom fit-out modules, achieving automated assembly for individual spaces through digital connectivity across the design, manufacturing, and construction processes.

The current status of research on the construction phase of industrialized construction can be summarized as follows. First, information communication aims to improve visibility, transparency, and collaboration by standardizing component naming and ensuring data interoperability among stakeholders. Challenges such as inefficient information transfer and potential data loss can be addressed through the implementation of blockchain and IoT platforms. Second, construction scheme planning utilizes VR, BIM, and other digital tools for schedule estimation, performance tracking, and disruption detection. Dynamic risk modeling, in particular, reflects the interrelationships between risk variables and their impact on assembly performance. Third, logistics management employs algorithms and simulations to assess the economic and environmental impacts of supply chain solutions. Fourth, safety monitoring integrates digital technologies to enable hazard assessment and mitigation, though issues related to coverage and data transmission require further attention. Finally, automated assembly focuses on robotic assembly and the use of technologies such as AR and VR to enhance assembly practices in automated environments.

4.4. Operation and Maintenance Phase

4.4.1. Predictive Maintenance

Predictive maintenance is a fundamental strategy in building operation that leverages data to predict potential problems in building facilities. Through systematic monitoring and data analysis, this approach facilitates proactive maintenance or repair interventions, preempting equipment failures or performance declines. Predictive maintenance is widely used in industrialized construction, where it aims to reduce downtime, improve equipment reliability, and ultimately reduce operating costs.

Predictive maintenance begins with meticulous data collection and monitoring. Utilizing modern mapping tools or sensors proves instrumental in this endeavor. Valinejadshoubi et al. [91]

integrated sensor data with BIM to effectively visualize structural health assessment components. Similarly, Brusa [92] showcased how modern mapping tools, such as unmanned aerial systems, digitally captured physical building data and features to evaluate building damage for emergency management purposes. Given the diversity in building types and materials, tailored data collection and monitoring programs are imperative. For instance, Asso et al. [93] adopted varied monitoring techniques for reinforced concrete beam half-joints, encompassing traditional inspection systems alongside emerging structural health monitoring techniques. Moreover, Sathurusinghe et al. [94] underscored the versatility of digital technologies in structural health monitoring, utilizing laser scanning and digital image analysis to continuously monitor the health of precast concrete bridges under diverse hydraulic conditions.

The digital twin model emerges as a pivotal tool for predictive maintenance, furnishing enhanced predictive capabilities while mitigating modeling uncertainties. The model significantly improves the predictive accuracy of vulnerability curves. For example, Praticò et al. [95] introduced the PRESSAFE-disp (PRecast Existing Structure Seismic Assessment by Fast Evaluation displacements) methodology, which involves collecting a wide range of data related to prefabricated buildings to create a comprehensive database. By categorizing these data, the methodology expedites seismic loss assessment and retrofitting decisions for large-scale prefabricated buildings. For prefabricated concrete bridges, Rojas-Mercedes et al. [96] developed a digital twin model integrating structural health monitoring with computational finite element modeling, enabling the formulation of seismic fragility curves to underpin post-disaster decision-making strategies. These advancements underscore the significance of predictive maintenance in refining operation practices, where the proactive identification of potential issues hold paramount importance. However, existing studies primarily focus on individual project types, necessitating more generalized methodologies.

4.4.2. Sustainable Operation

Building sustainability management is the application of sustainability principles to minimize environmental impacts, while providing a comfortable, healthy, and sustainable built environment. In addressing carbon emissions, it is imperative to verify the efficacy of carbon reduction strategies through rigorous monitoring and data acquisition. For instance, Cid et al. [97] developed an acquisition system based on Supervisory Control and Data Acquisition (SCADA), integrated with a single-wire bus network to monitor the energy efficiency of building envelopes. This system underwent validation to analyze the thermal behavior of concrete slabs reinforced with phase-change material, offering insights to enhance energy efficiency.

At the level of specific carbon reduction methods, Zanni et al. [98] advocated retrofit interventions employing cross-laminated timber panels, coupled with the sensor-based monitoring of building performance to achieve material carbon reduction. Addressing building material reuse, Dervisha et al. [99] proposed a numerical guide addressing the scarcity of data concerning reused building components. In the realm of noise reduction, Kraus et al. [100] utilized digital sound level meters to identify noise sources in precast buildings surpassing prescribed limits. Moreover, Dy Buncio [101] established digital replicas of industrial buildings by integrating BIM data with sensors and historical facility data. Nonetheless, prioritizing the owner's occupancy experience remains an ongoing challenge in building operations and maintenance.

The current state of research on the operation and maintenance phase of industrialized construction can be summarized as follows. First, predictive maintenance leverages data collection and monitoring through sensors and BIM to anticipate equipment failure or performance degradation. Digital twins can further enhance predictive accuracy and inform maintenance strategies. Second, sustainable operation aims to minimize environmental impacts through strategies such as monitoring energy efficiency retrofits, implementing carbon reduction methods, and promoting material reuse solutions. The research has integrated digital replicas to support performance monitoring and validate carbon reduction tactics. However, challenges remain in comprehensively addressing owner experience priorities alongside sustainability goals in operations.

5. Research Gaps and Future Directions

5.1. Design Phase

Currently, the trend in applying digital technologies in the design phase of industrialized construction emphasizes the integration of innovative design methods, such as parametric design and discrete design, with digital tools. The objective is to support the efficient design and optimal fabrication and assembly of complex geometrical forms, thereby enhancing building performance. These design methods, combined with techniques such as performance-driven optimization and differential geometry, enable designers to efficiently explore optimal solutions under manufacturing and assembly constraints. Moreover, performance simulations and assessments, such as energy analysis and life cycle assessment, have been incorporated into the design process, enabling designers to optimize the energy efficiency and environmental impact of buildings from an early stage. Future research directions include the following:

- While parametric and discrete design have enabled the realization of complex geometries and non-standard forms, further research into materials and the refinement of production processes for precast elements is needed for commercial production. Currently, wood and composite materials are considered ideal for discrete design [21]. Future research should systematically compare the suitability of different materials and investigate methods for designing large-scale, complex prefabricated concrete components.
- It is reported that the current IFC standard has limited support for information related to industrialized construction. Therefore, further research on open data standards and tools, such as an information delivery manual, is necessary to improve interoperability between digital design and the subsequential production tasks.
- One of the key barriers to applying LCA in the design process is the lack of accurate and comprehensive data, particularly regarding the environmental impacts of building systems. Future research can enable users to create their own online databases of construction systems. This will offer more flexibility in accessing and exchanging environmental impact information.

5.2. Production Phase

The trajectory of research concerning digital technologies within the production phase of industrialized construction is through the amalgamation of advanced manufacturing technologies and digital tools. On the one hand, emerging technologies like 3D printing and CNC enable the fabrication of customized precast elements with intricate geometries and textures. On the other hand, digital tools such as digital twins and human–computer collaboration find an extensive utilization in improving production flexibility, to contend with uncertainties and fluctuating demands. Furthermore, advanced measurement technologies have been seamlessly integrated to automate the inspection of element dimensions and surface quality. Subsequently, potential future research directions can be delineated as follows:

- While 3D printing technology substantially economizes on manpower, enhancing efficiency and curbing material wastage, its comparative slowness and higher cost vis-à-vis mass production pose challenges. Additionally, the necessity for the manual assembly of customized parts at construction sites further escalates construction cost. Hence, research endeavors can focus on synergizing robotics with 3D printing to automate the assembly of individual components to facilitate mass customization.
- Human–robot interaction technology within the production stage remains primarily experimental, with limited participation, predominantly from individuals possessing experience [53,54]. Concerning kinematics, the precision of robot movements and their maneuverability directly influence production process efficiency. Therefore, the

kinematic performance of robots should be further investigated, and the application scope of human–robot interaction should be expanded in industrialized construction.

5.3. Construction Phase

Current research focuses on digitization, intelligence, and automation throughout the construction process. Cutting-edge technologies such as the IoT and AI are extensively harnessed for intelligent monitoring, predictive analytics, and the proactive optimization of construction progress, logistics, and safety protocols. Concurrently, industrial robots are adopted to propel the adoption of customization and automated assembly. Consequently, prospective avenues for future research can be delineated as follows:

- Effective logistics planning necessitates the aggregation of voluminous data encompassing variables such as vehicle types, load capacities, and road tolls. Presently, an empirical understanding of the actual vehicle kilometers (vkm) attributed to the plethora of vehicles within the industry remains limited, with available information predominantly relying on speculative inference [75]. Future work can integrate a logistics information integration platform and optimization models to improve component delivery solutions.
- Compared with risk assessment, relatively scant attention has been devoted to automated real-time risk mitigation strategies. Existing risk management protocols predominantly rely on manual intervention [84]. Thus, prospective investigations should explore the synchronization of safety–risk prediction mechanisms with on-site construction activities. Additionally, devising methodologies to implement an automated risk response system warrants substantial efforts.

5.4. Operation and Maintenance Phase

The prevailing trajectory in the application of digital technologies within the operation and maintenance phase of industrialized construction is to realize intelligent operation and maintenance management alongside sustainability imperatives. On one front, researchers are leveraging BIM, digital twins, and sensors to facilitate the real-time monitoring, assessment, and prognostication of structural health conditions. On another front, the amalgamation of monitoring data with digital models facilitates comprehensive building sustainability management initiatives. These include energy efficiency analyses, noise source identification, and maintenance decision-making. Prospective directions for future research can be delineated as follows:

- Existing digital twin models cater to specific building types, facilitating structural condition monitoring and predictive maintenance endeavors [95]. Future efforts should further improve the comprehensiveness of model data, aggregating information about earthquake magnitudes and the number of buildings that collapsed in accidents. Such a resource will aid in creating a multifunctional digital twin system adaptable to a wide range of industrialized construction projects.
- Present operation and maintenance practices prioritize predictive maintenance strategies geared towards enhancing the overall living experience. However, these approaches often overlook the nuanced aspects of occupants' daily lives, such as commuting experiences and the rational allocation of building spaces. Future interventions could simulate user experiences and solicit feedback on living spaces, thereby enhancing occupant satisfaction and well-being.

6. Conclusions

This study reviewed 173 journal articles on digitalizing industrialized construction, focusing on academic articles published from 2014 to 2023 to capture the most recent advancements. Several key findings emerged from this systematic review. First, there is a clear upward trend in research interest related to digital technologies in industrialized construction, primarily addressing the design, production, and construction phases, with less focus on the operation and maintenance phase. Second, the core functions of digital technologies across all project phases are enhancing efficiency, flexibility, visualization, and intelligence. Third, interdisciplinary technology integration is essential, with data acquisition, modeling, and simulation forming the digital foundation across all stages. Fourth, significant shortcomings remain in the current application of digital technologies, with common issues such as data interoperability, standards, and cost control requiring further investigation.

This review significantly contributes to the existing body of knowledge by elucidating the current status and emerging research trends in the application of digital technologies within industrialized construction settings. It advances our understanding by detailing the role of digitalization across various project stages, providing a comprehensive analysis that highlights its impact and potential benefits. Furthermore, this review identifies prospective research directions, paving the way for future studies to build on these insights. The findings of this study not only enhance the theoretical framework surrounding digitalization and industrialization in construction but also serve as a catalyst for promoting their broader adoption within the industry.

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