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Recent research developments in intelligent methodologies for prefabricated construction

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Abstract: The ongoing advancement in intelligent construction technology is driving the intelligent transformation of the traditional construction industry. Prefabricated construction, noted for its efficiency, environmental friendliness, and reduced labor requirements, has attracted significant attention. While research on intelligent construction in the prefabricated industry is expanding, comprehensive literature reviews analyzing and synthesizing these findings remain limited. To this end, this article undertakes a systematic literature review, analyzing 114 papers closely related to intelligent methodologies in prefabricated construction. It encompasses the prefabricated construction lifecycle: design, manufacturing, construction, and operations and maintenance. Statistical analysis reveals that building information modeling (BIM), the genetic algorithm, and laser scanning have emerged as the three most prevalent intelligent methodologies in this field. Furthermore, we conducted an in-depth literature analysis and identified the current research gaps. Future directions are suggested, including generative artificial intelligence design, dynamic production scheduling optimization methods, fully automated process quality inspection methods, long-range transportation methods for electric vehicles, low-cost digital twin monitoring techniques, and multidimensional, comprehensive lifecycle management systems. This review aims to provide readers with a clear understanding of recent research developments in intelligent methodologies for prefabricated construction, thereby facilitating the intelligent transformation of the traditional construction industry.

Keywords: intelligent construction; prefabricated construction; building information modeling; genetic algorithm; laser scanning

1. Introduction

With the rapid development of modern science and technology, particularly the emergence of artificial intelligence, the traditional construction industry is undergoing a profound transformation [1,2]. Intelligent construction, although lacking a unified definition, fundamentally signifies the amalgamation of modern information technologies with architectural techniques [3]. It encompasses the life cycle or key stages of the construction process, focusing on sensing, learning, reasoning, analyzing, decision-making, execution, and control [4]. Additionally, intelligent construction dynamically adapts to environmental changes to optimize specific objectives, thereby enhancing the quality and efficiency of construction projects and serving the entire life cycle [5,6].

The prefabricated industry is dominated by the prefabricated construction method, which refers to manufacturing the construction components in factories based on precise design data, passing quality inspection, then transporting them to the construction site for final assembly [7]. This method significantly enhances production efficiency [8], reduces construction timelines [9], curtails labor demand [10], and offers environmental benefits through material reduction, reusability, adaptability, and recyclability [11]. In China's 14th Five-Year Plan, the country set a goal of, by 2025, approximately 30% of new buildings' being prefabricated constructions [12]. Given that China's new buildings comprise nearly half of the annual global area of new construction [13], this trend poses substantial challenges to intelligent construction's capabilities in prefabricated industry.

While a significant body of research exists on the intelligent construction technology, there is a notable dearth of literature reviews in this domain. Xu *et al*. outlined the application of intelligent construction in road compaction [4]. An *et al*. reviewed the applicability of intelligent construction technology, including its priorities and future research directions [5]. These studies, however, predominantly focus on the road sector or provide a broad overview, leaving a gap regarding the literature reviews about intelligent construction in the prefabricated industry. This gap hinders the promotion and implementation of prefabricated construction. Therefore, this review aims to comprehensively elucidate the research hotspots and frontiers of intelligent construction in the prefabricated industry, thereby facilitating the intelligent transformation and progression of the traditional construction industry. It is worth noting that this article selects prefabricated components as the object of its literature search to avoid too many documents that cannot be effectively analyzed.

2. Literature collection and preliminary analysis

2.1. Literature collection

In this study, the systematic literature review (SLR) method was used due to its rigorous and explicit methodology, which enables the comprehensive identification, evaluation, and synthesis of extant knowledge on a specific subject [14,15]. First, an initial literature search was conducted in the ScienceDirect database because it is one of the biggest databases and covers a wide range of scientific publications [16]. An advanced search with "Title, abstract or author-specified keywords" was executed in the ScienceDirect database with the search string set to ("prefabricated component" OR "assembled component" OR "precast component" OR "modular component") for publications with no time limits and set to research and review articles only. This search yielded 418 records. To increase the literature search's comprehensiveness, a similar search was run in the Web of Science, a database containing the world's most influential journals and highly cited literature [17]. This search yielded a result of 297 records. After merging the identification results from both databases, a total of 715 records were obtained. By employing EndNote to eliminate duplicates, 663 records were retained as the initial sample for this study. Then, by screening the article topics, we excluded papers with topics irrelevant to the construction industry. Through the initial screening, 180 records were removed, and 483 records were retained. The remaining 483 records were then further screened through full-text reading using the following inclusion criteria:

(1) The main research object must be prefabricated components.

(2) The paper must include methodologies related to intelligent construction, such as building information modeling (BIM), the Internet of Things (IoT), artificial intelligence (AI), or other advanced technologies.

Among the 483 records, 392 that did not comply with the inclusion criteria were excluded, and 91 were retained. Relying solely on abstract-based literature retrieval presents certain limitations, however, as it may inadvertently exclude some important papers. To address this, this study also adopted a snowballing search strategy to supplement our results with significant articles that fell outside the scope of the abstract search but were relevant to the research theme [18]. From the initial set of 91 papers selected for snowball searching, an additional 23 papers meeting the inclusion criteria were identified. Consequently, a total of 114 papers were collected for subsequent analysis. Figure 1 presents a flowchart of the literature collection 1.

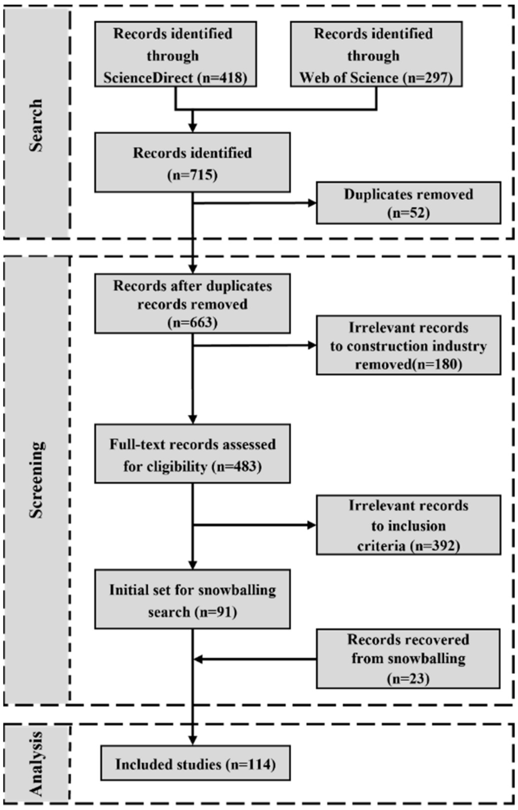


Figure 1. Flowchart of literature collection.

2.2. Preliminary analysis of literature

This paper's analysis of annual publication trends from 114 selected records, detailed in Figure 2, reveals a significant trajectory in academic engagement and research focus. In the initial years (2001–2007), the frequency of publications remained quite low, indicating that the topic was emerging and had not yet gained significant traction within the academic community. This period could be characterized by foundational research and early exploration of the potential of intelligent construction methodologies. From 2010 onward, we observe a fluctuating increase in publications, with a noticeable uptick in 2018. This could reflect advancements in relevant technologies, such as BIM, IoT, and AI, which may have provided new opportunities and tools for researchers to delve deeper into the subject. The absence of any publications in 2011 and 2014 might be an anomaly, or it could suggest a transitional phase in research focus or methodologies. The years 2020–2023 show a marked surge in publications, which could be attributed to several factors, such as increased funding, wider recognition of the benefits of intelligent construction methodologies, and a stronger emphasis on sustainability and efficiency in the construction industry. The sharp rise during this period signifies the maturation of the field as a significant area of scholarly interest. Since the collection period for this article ends in January 2024, the count of four publications in just the first month of 2024 points to a continued strong interest and active research in the field. It indicates that the overall annual count in 2024 may well surpass those of previous years once data for the entire year becomes available. In addition, the calculation results show that 72.8% of the 114 total papers were published from 2020 to January 2024, which verifies that this issue is becoming increasingly popular.

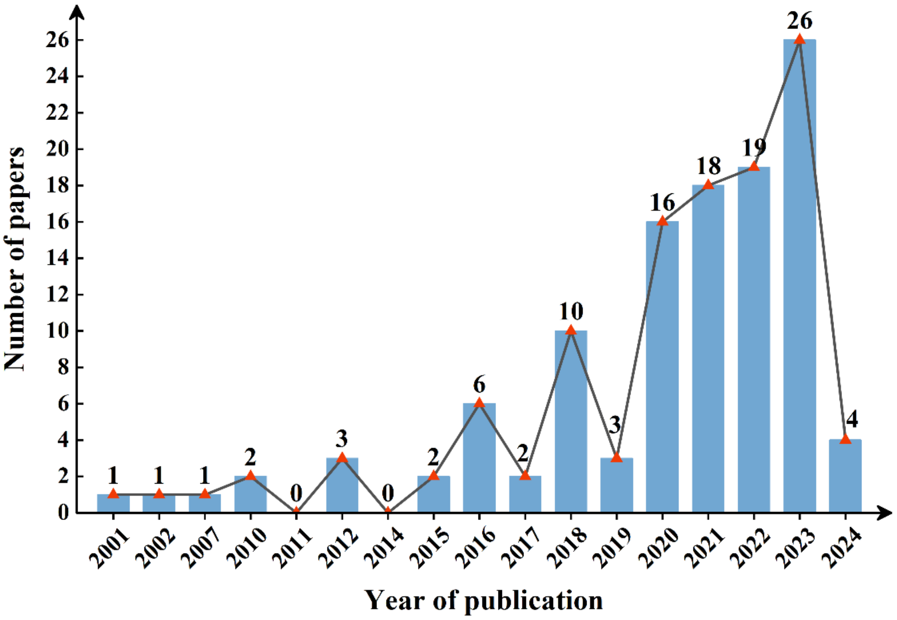


Figure 2. Annual research publication closely related to intelligent construction in the prefabricated industry.

Beyond analyzing annual publication trends, intelligent methodologies employed in the 114 selected papers were also counted, as illustrated in Figure 3. Statistical analysis revealed that the three most prevalent methodologies used were BIM, genetic algorithm, and laser scanning.

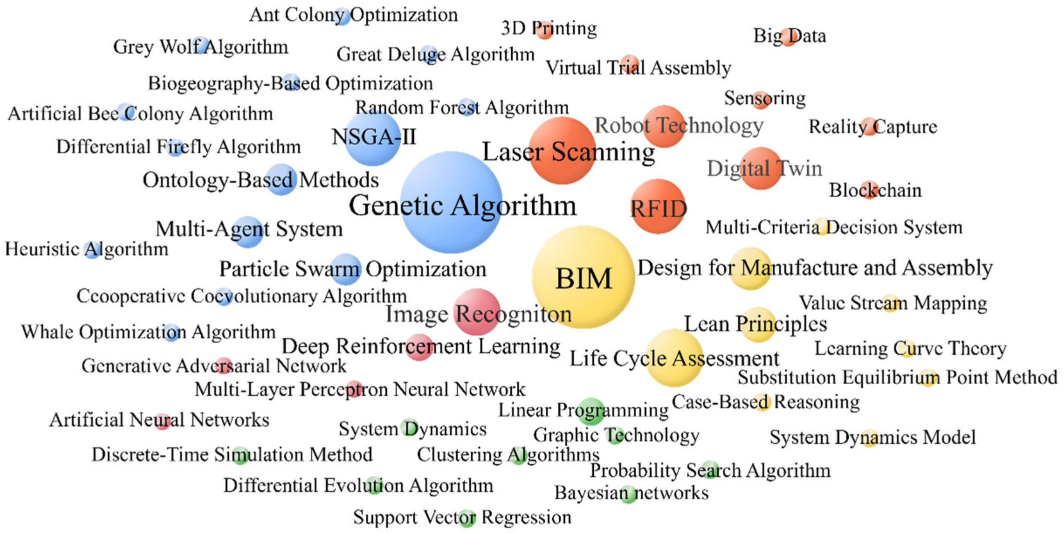


Figure 3. Intelligent construction methodologies employed in the 114 selected papers.

According to the prefabricated construction life cycle, further analysis of intelligent methodologies encompasses four stages: design, manufacturing, construction, and operation and maintenance, each of which will be discussed individually.

3. Detailed analysis around the prefabricated construction lifecycle

3.1. Intelligent design methods

3.1.1 Design-optimization methods

BIM has transformed the design of prefabricated components by providing a digital representation that enhances traditional computer-aided design (CAD) [19]. A striking feature of BIM is parametric design, in which all entities in BIM are presented in the form of components. Consequently, any modification in the design automatically updates the associated elements, significantly streamlining the designers' work and enhancing efficiency [20]. Zhang *et al*. used BIM through Revit software for 3D modeling, demonstrating its effectiveness in managing complex prefabricated components within a modular grid system [21]. Deng and Zou further advanced BIM applications in deep design and component optimization, demonstrating the technology's versatility [22,23]. Tian *et al*. emphasized the adaptability of BIM in handling various prefabricated components, considering aspects of design, construction, and installation [24]. Li *et al*. introduced automatic modeling for precast concrete components, greatly improving the efficiency of virtual trial assembly (VTA) [25].

Complementarily to BIM, heuristic algorithms have proven powerful tools for optimizing the design of prefabricated components. These algorithms are capable of addressing complex design challenges and providing near-optimal solutions when exact solutions are impractical [26]. De *et al*. employed genetic algorithms to optimize the balance between the cost and structural performance of concrete floor slabs [26]. Li and Zhu applied immune genetic algorithms for the optimal placement of walls and beams, demonstrating the potential of heuristic methods in structural optimization [27]. Stindt *et al*. used metaheuristic techniques in a modular approach, which significantly reduced carbon emissions during the mass production of structural elements [28]. Kumi *et al*. employed genetic algorithms to balance environmental effects and costs in the design of prefabricated columns, thereby integrating environmental and economic considerations [29]. Wang *et al*. combined quality function deployment with ant-colony optimization to enhance the quality assurance of prefabricated components [30].

The integration of BIM with heuristic algorithms facilitates a synergistic approach that leverages the strengths of both technologies in component design. Xu *et al*. developed a system that integrates BIM with the random-forest algorithm to automatically classify and code components [31]. Lao *et al*. combined BIM with NSGA-II-GD to standardize and enhance the design of prefabricated components [32].

Furthermore, mathematical optimization and deep learning techniques, such as linear programming and generative adversarial networks (GANs), are also being applied in design optimization. Hernández *et al*. used linear programming to optimize the design of prestressed concrete beams [33]. Liu *et al*. applied deep learning, specifically GANs and deep reinforcement learning, to automate conflict resolution in steel-bar design, thereby improving both its efficiency and accuracy [34].

This paper presents a framework for the BIM-based design optimization of prefabricated components, as depicted in Figure 4. The framework underscores BIM's comprehensive modeling capabilities, support for collaborative work, real-time updates, and data-driven optimization approach, positioning BIM as an indispensable tool in the optimization process within the prefabricated construction industry. While BIM plays a pivotal role in the optimization of design processes, it faces several data-management and interoperability challenges. These include ensuring data consistency, managing version-control conflicts, enhancing software interoperability, implementing robust security measures, and meeting comprehensive training requirements. These factors are crucial for maximizing the effectiveness of BIM and ensuring the success of projects. Heuristic algorithms, which are instrumental in resolving complex design challenges, also pose certain limitations; they often require extensive parameter tuning and significant computational resources, which may hinder their scalability across larger or more complex projects. The integration of BIM with heuristic algorithms represents a strategic convergence that exploits the strengths of both approaches to enhance design optimization. This integration, however, is not without its difficulties, particularly when it comes to data integration and model optimization, which require deeper investigation to overcome the existing limitations. On another front, mathematical optimization techniques like linear programming provide targeted solutions for specific design objectives, offering a high level of precision. Similarly, deep learning methods facilitate the automation and improve the accuracy of design processes. Still, both approaches demand considerable computational power and specialized knowledge in model training, which can be barriers to their widespread adoption.

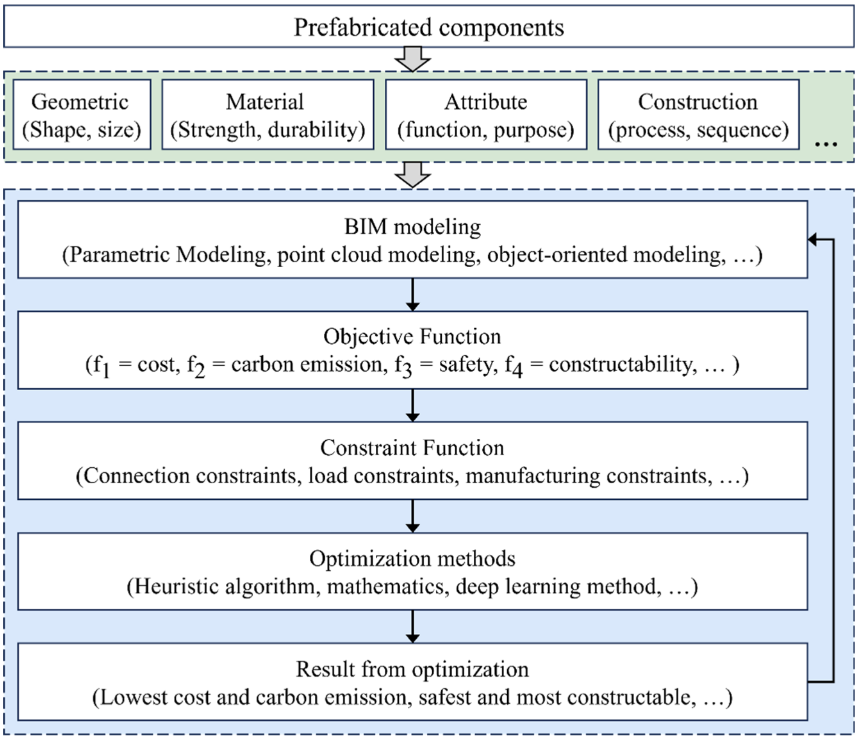


Figure 4. Framework of proposed BIM-based design optimization method for prefabricated components.

In conclusion, the combined use of BIM technology, heuristic algorithms, mathematical optimization, and deep learning offers a comprehensive approach to design optimization in the realm of prefabricated construction. Future research should focus on overcoming the technical challenges associated with these technologies and investigating innovative methods to further enhance their efficiency and effectiveness in the construction industry. This multifaceted approach not only broadens the scope of possibilities but also opens new avenues for advancing construction technology.

3.1.2 Design data transformation methods

The conversion of design data into manufacturing data is a pivotal stage in the prefabrication process. Design for Manufacture and Assembly (DfMA) principles play a crucial role in simplifying product design for seamless manufacturing and assembly. Yuan *et al*. proposed a parametric design process aligned with DfMA principles that effectively bridges the gap between design and manufacturing data [20]. Similarly, Qi *et al*. introduced a framework integrating BIM with ontology-based methods to enhance the DfMA process, particularly in conflict detection and compliance checks, ensuring the accurate and efficient translation of design data into manufacturing specifications [35]. The practical implementation of these principles is evident in their application by Kim *et al*. in bridge construction in the UK [36].

During the data-transformation phase, the data conversion format is crucial to minimize information loss. Liu *et al*. discussed the integration of BIM with (Bundesvereinigung Bausoftware) BVBS codes to optimize the automated prefabrication process of steel reinforcement, highlighting the accuracy and efficiency of this method in large-scale construction projects [37]. Wang's exploration of data-exchange formats between BIM software and prefabrication machinery, particularly for steel rebars and trusses, underscores the importance of seamless data transfer [38].

Additionally, 3D printing technology is seen as a promising solution to enhance the flexibility of off-site prefabrication. Its ability to manufacture customized components without additional cost and with greater design freedom is noteworthy. He *et al*. combined BIM with 3D printing technology, presenting a novel approach for efficiently and accurately translating design data into manufacturing processes for prefabricated components [19].

Thanks to the visualization of BIM and DFMA's integrated consideration of design and manufacturing, design data and production data are no longer isolated but interconnected. Currently, existing research on the transformation of design data into production data focuses primarily on reducing errors and enhancing conversion efficiency. Data transformation, however, should also pay more attention to cost and privacy because focusing on the cost of data transformation can help companies optimize resource allocation, reduce production costs, and improve efficiency. Addressing privacy concerns in data transformation can help companies establish robust information-protection mechanisms to safeguard their core business interests and customer interests. Furthermore, enhancing the universality and standardization of data conversion formats is crucial. Doing so would improve interoperability between different software systems, promoting seamless data exchange.

3.2. Intelligent manufacturing methods

3.2.1 Facility layout planning methods

Facility Layout Planning (FLP) is instrumental in optimizing production efficiency, cost minimization, and the use of space in prefabricated construction. Despite its significance, research on FLP for prefabricated factories remains relatively scarce. To address this gap, Yang and Lu conducted simulations and optimizations of real-world cases, comparing various layouts to determine the optimal configuration for prefabricated components [39]. Their study explored layouts, including process layout, product layout, combination layout, fixed-position layout, and cellular layout. The results indicated that the cellular layout yielded the highest output, while the product layout demonstrated superior economic performance in specific cases, offering valuable insights into production-line layout for prefabricated component manufacturing.

FLP problems are inherently complex, often classified as nondeterministic polynomial (NP) hard problems. To tackle these challenges, Zhang *et al*. developed a mathematical model for dynamic FLP and devised a particle swarm optimization-based algorithm for dynamic prefabricated component site layout [40]. Their approach combines a multi-stage layout and two-step optimization framework, providing a robust solution for optimizing facility layouts in prefabricated construction. Additionally, Lu and Zhu integrated FLP with prefabricated component installation, employing genetic algorithms (GAs) to solve the problem effectively [41].

3.2.2 Production-scheduling optimization methods

Production-scheduling optimization is pivotal to ensuring the timely delivery of prefabricated components, building upon efficient facility-layout planning [42]. Genetic algorithms (GAs) have been prominently used in flowshop scheduling model (FSM), as indicated by the representative research literature summarized in Table 1.

Table 1. Representative research literature on by using GAs to solve FSM problems.

Optimization objectives	Considered primary variables	Literature
Minimization of the tardiness and earliness penalties	Working time and operation types	Chan and Hu. [43,44]
Minimization of the makespan and tardiness penalties	Buffer size between production stations	Ko and Wang. [45]
Minimization of the delivery penalty, type change of precast components during production	Multiple production lines	Yang *et al.* [46]
Minimization of the makespan, contract penalty, and storage cost, workstation idle time, material re-dispatch complexity and workload, and over-assigned time for production emergencies	Rescheduling using the over-assigned time	Ma *et al.* [47]
Minimization of the total penalty cost of earliness and tardiness	Process connection and blocking	Dan *et al.* [48]
Minimization of the sum of the production cost and early penalty cost and the days with two shifts	Multi-shift production	Dan *et al.* [49]
Minimization of the makespan, and total penalty cost of earliness and tardiness	Parallel work of serial machines	Liu *et al.* [50]
Minimization of the processing cost, transportation cost, penalty cost for the tardy quantities, and processing costs and transportation costs for demand that cannot be completed on time	Multiple fabrication shops	Ho *et al.* [51]

The above existing methods, however, show limitations in dynamic environments, where factors like labor productivity and equipment availability are variable. To address these challenges, Kim *et al.* developed a dynamic model using discrete-time simulation methods, incorporating new rules to account for deadline uncertainties and minimize delays in real time [52]. Similarly, Du *et al.* proposed a dynamic scheduling model that considered deadline advancements, urgent component insertions, and order cancellations [53]. Interrupt management, a widely applied technique in production planning, dynamically adjusts schedules to align with evolving environmental goals and constraints. Zhang *et al.* proposed a three-tier scheduling interruption management model and applied an improved NSGA-II algorithm for solving it [54].

In addition to GAs, alternative methods have shown efficacy in solving FSM problems for prefabricated component production. Jiang *et al.* devised a hybrid model for scheduling both on-demand and stock-based components using a whale optimization algorithm to minimize total lateness and early deliveries [55]. Wang *et al.* integrated resource scheduling with machine maintenance, employing a differential evolution algorithm to minimize project-duration uncertainty and enhance cost-effectiveness and production efficiency [56]. Du and Li used deep reinforcement learning, specifically the Double Deep Q-Network (DQN) algorithm, to optimize scheduling in prefabricated concrete production [57].

Furthermore, various optimization frameworks and algorithms have been proposed to address specific challenges in production scheduling. Chang and Dai designed a production-transport batch coordination model, applying the multi-objective discrete grey-wolf algorithm to achieve on-time delivery and improved management efficiency [58]. Wang *et al.* used a multi-agent system (MAS) and genetic algorithms to synchronize production scheduling and resource allocation, with the potential for real-time production control development [59]. Xu *et al.* proposed an automated optimization framework by integrating BIM, graphic technology, a database, and interface development to bridge the technological gap between designers and manufacturers [60]. Additionally, Niu *et al.* introduced a two-stage cooperative coevolutionary algorithm (TS-CCEA) to address distributed group FSM scheduling problems with blocking and carryover sequence-dependent setup time constraints [61]. Wang *et al.* presented a dual-layer simulation-GA hybrid model to handle complex production uncertainties and ensure on-time delivery [62]. Du *et al.* incorporated lean construction principles and value-based management into prefabricated component production, using biogeography-based optimization (BBO) for scheduling [63]. Ruan *et al.* enhanced the scheduling model by considering resource constraints and enterprise decision coefficients [64]. Finally, Qin *et al.* introduced a multi-objective optimization algorithm aimed at reducing costs and enhancing efficiency [65].

In summary, GAs are renowned for their robust optimization capabilities, making them ideal for tackling complex scheduling problems with multiple objectives. Their ability to efficiently explore vast solution spaces and identify near-optimal solutions is notable. Still, GAs may encounter challenges associated with high computational complexity and resource demands. Complementary optimization techniques, such as hybrid algorithms and deep reinforcement learning, offer alternative approaches to addressing specific scheduling challenges. While these methods may excel in certain scenarios, they often require meticulous parameter tuning and domain-specific expertise.

Moreover, current research predominantly focuses on minimizing completion time, managing delay penalties, and enhancing production efficiency. Future developments, however, could consider additional constraints to further improve scheduling optimization:

(1) Sustainability Constraints: Incorporating environmental factors like carbon emissions and energy consumption into scheduling-optimization models to promote sustainable practices in prefabricated construction.

(2) Resource Constraints: Addressing limitations in material availability, equipment capacity, and workforce availability to optimize resource use and mitigate production bottlenecks.

(3) Supply-Chain Integration: Integrating supply-chain considerations, such as material procurement, transportation logistics, and inventory management into scheduling optimization to ensure seamless coordination across the entire production process.

(4) Digitalization and Automation: Harnessing emerging technologies, such as artificial intelligence, machine learning, and IoT, to develop automated scheduling solutions capable of adapting to real-time data and autonomously optimizing production processes.

(5) Stakeholder Collaboration: Enhancing collaboration and communication among project stakeholders—including designers, manufacturers, suppliers, and contractors-to streamline decision-making and enhance overall project efficiency.

3.2.3 Manufacturing monitoring and improvement methods

In addition to scheduling, intelligent monitoring and optimization methods are also crucial in enhancing the manufacturing process. For instance, Ding *et al*. developed smart prefabricated concrete columns embedded with cement sensors filled with carbon nanotube (CNT)/nano carbon black (NCB) composites, enabling real-time monitoring of stress/strain states [66]. Ergen *et al*. integrated RFID and GPS technologies to track and locate prefabricated components, automating the tracking process to minimize errors and improve efficiency [67]. Tao *et al*. introduced an IoT-based greenhouse-gas emission monitoring system, using RFID and laser-sensing systems to collect and analyze carbon-emission data during prefabricated component production [10]. To address the COVID-19 pandemic, Ahmed *et al*. used prefabricated components to construct isolation facilities, employing a multi-layer perceptron neural network model to select optimal solutions [68]. Laser projectors serve as effective tools for guiding construction, reducing errors, and enhancing efficiency during the manual placement of semi-finished steel bars and embedded parts onto the mold platform. Figure 5 depicts the application scenario of the laser projector developed by the author's team in this article.

The above research on intelligent monitoring technologies can be classified into two main types based on the characteristics of the research object: invasive monitoring and non-invasive monitoring. *Invasive monitoring* involves modifying the research object to collect data, such as gathering position data from prefabricated components. Conversely, *non-invasive monitoring* directly acquires data through sensors without altering the object, such as collecting environmental data from prefabrication plants. Moreover, the reliability and efficiency of monitoring equipment, coupled with the accuracy and feedback capability of analysis algorithms, are essential for achieving timely and effective monitoring and adjustment feedback.

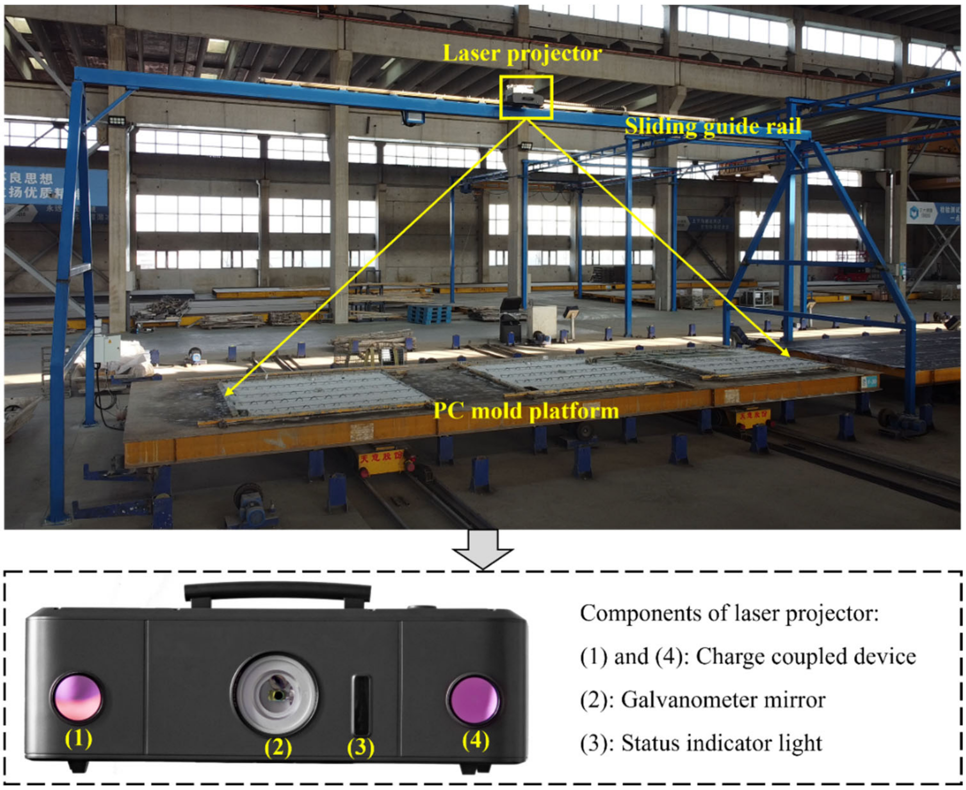


Figure 5. Application scenario of laser projector developed by the author's team for guiding construction.

The adoption of BIM emerges as a pivotal element in optimizing manufacturing processes, offering the potential to refine production precision and minimize errors, thereby fostering more efficient and cost-effective manufacturing processes. For instance, Jang and Lee’s study showcases BIM’s application in conducting comprehensive analyses across various phases of multi-trade prefabrication (MTP), aiming to bolster production efficiency and economic gains [69]. Similarly, Anane *et al*. and An *et al*. emphasize the integration of BIM with computational design tools and automated manufacturing assessment, respectively, demonstrating enhanced production efficiency and accuracy [70,71]. Furthermore, Chatzimichailidou and Ma’s research underscores the integration of BIM with modular construction and safety management, highlighting the focus on enhancing safety risk management in prefabricated component production [72].

Beyond the scope of BIM, however, other innovative methodologies also significantly contribute to the optimization of prefabricated component production. For example, Sirajudeen and Krishnan's application of lean principles and value stream mapping (VSM) reflects an augmentation in efficiency and production volume [73]. Zhang *et al*. introduced a novel approach using a multi-label classification loss equation and a probability search algorithm to control the positions of prefabricated components, enhancing prediction accuracy and convergence [74]. Tai *et al*.’s use of learning curve theory optimizes worker training and skill development, thereby augmenting production efficiency [75]. Additionally, Ye *et al*.’s employment of the WSR model and dynamic Bayesian networks facilitates the dynamic assessment and prediction of cost risks associated with prefabricated components [76].

In summary, while BIM plays a central role in optimizing manufacturing processes, various complementary methodologies, such as lean principles, advanced modeling techniques, and dynamic risk assessment models, contribute to further enhancing efficiency, accuracy, and risk management in prefabricated component production.

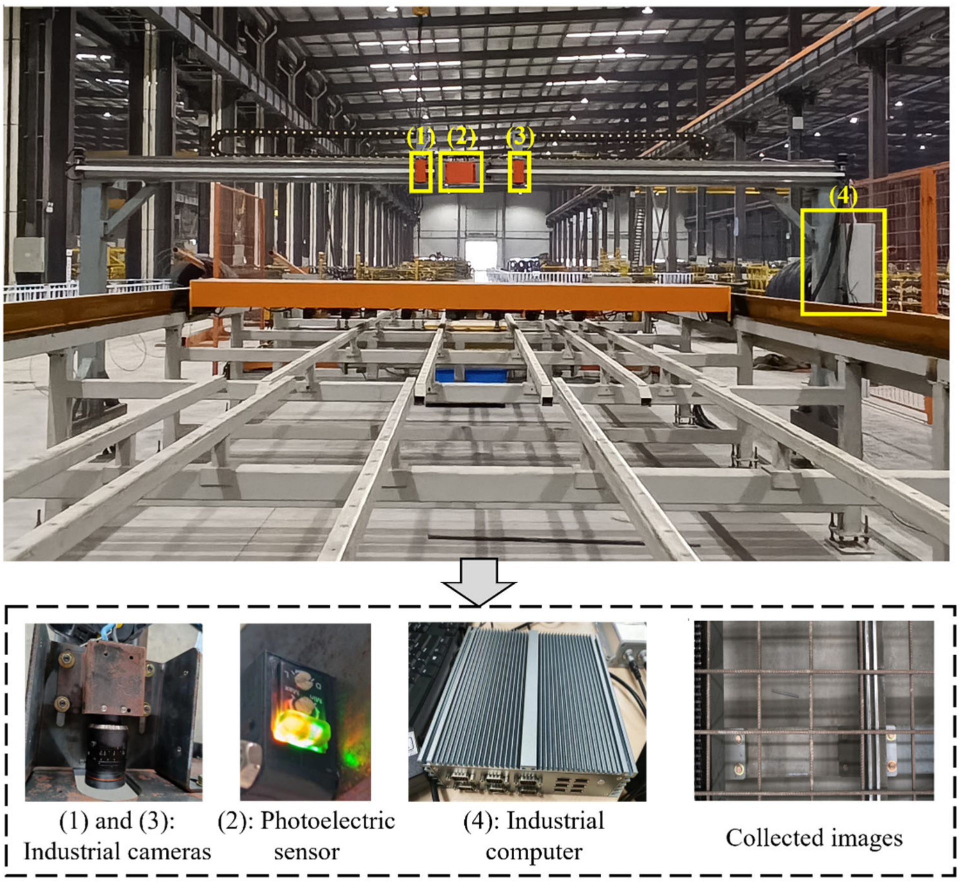
3.2.4 Product dimensional quality inspection methods

Product dimensional quality inspection (DQI) in prefabricated construction has undergone significant advancements, transitioning from traditional manual methods, which relied on tape measures, calipers, and rulers, to more automated techniques. These conventional methods, although widely used, were time-consuming and prone to errors due to their labor-intensive nature. In contrast, new detection methods leveraging 3D laser scanning and image recognition are gradually replacing manual detection processes [77]. Table 2 highlights the methods and errors identified in existing studies on DQI of prefabricated components.

Table 2. Methods and errors identified in existing studies on DQI of prefabricated components.

Method	DQI Error	Literature
3D photography-based point cloud model reconstruction	Average dimensional errors of length and width for special-shaped concrete prefabricated component are about 1.5 mm.	Shi *et al.* [78]
Laser scanning-based technique	The rebar spacing, the formwork dimension, the concrete cover, and the side cover of the tested specimen are estimated with discrepancies of 2.15 mm, 2.52 mm, 2.18 mm, and 3.12 mm on average, respectively.	Kim *et al.* [79]
Terrestrial laser scanning	Average error of 1.5 mm for precast concrete elements with geometry irregularities reinforced precast concrete bridge deck panels.	Wang *et al.* [80]
Colored laser scanning	Average difference of rebar positions was 0.9 mm	Wang *et al.* [81]
BIM and laser scanning	Average error of precast panel with 2.5 mm	Kim *et al.* [82]
BIM and laser scanning	Measurement accuracy of around 3.0 mm for dimension and position estimations	Kim *et al.* [83]
Image-based 3D reconstruction	Error is 0.21 mm for the aluminum pipe and 0.43 mm for the concrete column	Lee *et al.* [84]
Adaptive 3D imaging	Assist engineers to adjust data-collection locations and imaging parameters according to geometric complexities of prefabricated components	Kalasapudi *et al.* [85]

Table 2 indicates that achieving millimeter-level precision is sufficient to meet engineering inspection specifications, whether based on point cloud models or images. A common limitation in these studies, however, is the commencement of DQI after production completion, resulting in a lag in adjusting non-compliant products. To mitigate this issue, the authors developed a gantry device incorporating industrial cameras and photoelectric sensors for the synchronous detection of rebar spacing and dimensions during steel mesh production, as illustrated in Figure 6. This facilitates timely adjustments in the event of dimensional discrepancies, thereby reducing waste. Moreover, there is a growing need for further research into rapid and high-precision dimensional quality-inspection methods tailored for oversized prefabricated components, such as the rebar skeleton of prefabricated box girders.



(1) and (3): Industrial cameras

(2): Photoelectric sensor

(4): Industrial computer

Collected images

Figure 6. Real-time DQI device for steel mesh of prefabricated components developed by the author's team.

3.3. Intelligent construction methods

3.3.1 Transportation-optimization methods

Transportation is the delivery of finished products to the construction site. The optimization of the transportation stage includes two factors; one is the selection of transportation vehicles, transportation-route planning, and the transportation process, as shown in Table 3.

Table 3. Selected existing research in transportation-optimization factors.

Research subject	Research method	Research content	Literature
Transportation vehicles	Multiple linear regression based on real-world case data	Explore the actual carbon emission performance of BEV during transportation	Wang *et al.* [86]
	Artificial Neural Network	Develop an ANN-network-based model to estimate the carbon emissions of BEV	Wang *et al.* [87]

Table 3. *Cont.*

Research subject	Research method	Research content	Literature
Transportation-route planning	Knowledge-driven multi-objective optimization algorithm	Introduce a multi-frequency vehicle routing model to minimize total transportation cost and makespan	Qi *et al.* [88]
	Improved hybrid difference firefly algorithm	Construct a linear programming model to minimize transportation path and comprehensive cost	Zou *et al.* [89]
	Substitution equilibrium point method	Propose a transport vehicle deployment model to maximize the completion degree of transportation	Shi *et al.* [90]
	Improved artificial bee colony algorithm	Establish a special type of vehicle routing problem with time windows to minimize the sum of the energy consumptions of all vehicles	Li *et al.* [91]
Dynamic transportation process	Particle swarm optimization algorithm	Introduce a dynamic transportation planning model to minimize total ordering costs	Zhang and Yu. [92]

The outcomes in Table 3 underscore the efficacy of electric vehicles as substitutes for traditional fossil-fuel vehicles. The transportation of prefabricated components, however, diverges from passenger transportation, necessitating further investigation into enhancing its payload capacity and range. Moreover, transportation optimization transcends the mere consideration of the shortest routes, advancing toward more holistic approaches encompassing economics, energy efficiency, and overall effectiveness.

On the other hand, reasonable stacking and the intelligent supervision of prefabricated component transportation can improve transportation capacity and ensure the timely delivery of components, and its optimization is also indispensable. Wang *et al.* approached the vertical stacking problem of prefabricated panels as a bi-objective combinatorial optimization problem [93]. They used a mixed-integer programming model and NSGA-II to optimize vertical stacking schemes, improving transportation efficiency and safety. Shewchuk and Guo proposed a lean method for panel stacking, sorting, and positioning during the transportation of prefabricated wall panels [94]. Additionally, Valinejadshoubi *et al.* developed a tracking system comprising data-acquisition modules to assess the structural condition of prefabricated components during transportation [95]. Ahn *et al.* implemented geographical fence-based GPS data analysis and support vector regression to accurately estimate transportation costs [96].

3.3.2 Assembly improvement methods

In prefabricated construction, the assembly stage emerges as a pivotal phase, ensuring the reliability of component connections and overall construction safety. The fusion of robotics and digital technologies has propelled advancements in assembly processes. Pioneering studies by Shu *et al*. [97] and Gao *et al*. [98] have introduced robotic assembly methods and BIM-based systems that have enhanced safety and efficiency, particularly in challenging environments like hospitals during the COVID-19 crisis. These endeavors underscore a broader trend toward automation in construction, extending to additive manufacturing applications, as explored by Bhatt *et al*. [99].

Meanwhile, precision and efficiency remain paramount in component assembly, driving the development of innovative methods to tackle these challenges. Techniques encompassing dynamic load calculations for tensioning, as proposed by Yang *et al*. [100], as well as advanced imaging [104] and reality-capture technologies [101,106] for precise installation and joint design, signify a shift toward leveraging intelligent tools to enhance assembly outcomes. Noteworthy are the integration of genetic algorithms and simulated annealing by Liu *et al*. [105] to optimize assembly operations, highlighting the ongoing refinement of computational strategies in construction. Furthermore, models driven by case-based reasoning, data-driven adaptive decision-making, and BIM-centric methodologies [12,103,107] have emerged as effective tools to bolster accuracy and efficiency.

Safety considerations loom large, given the intricate nature of construction environments. Vision-based trajectory monitoring [108] and 3D laser scanning [109,110] enhance the accuracy of component placement and overall site safety. Moreover, the adoption of hazard identification and risk assessment methods helps preemptively address safety risks during assembly, ensuring a secure construction process [111].

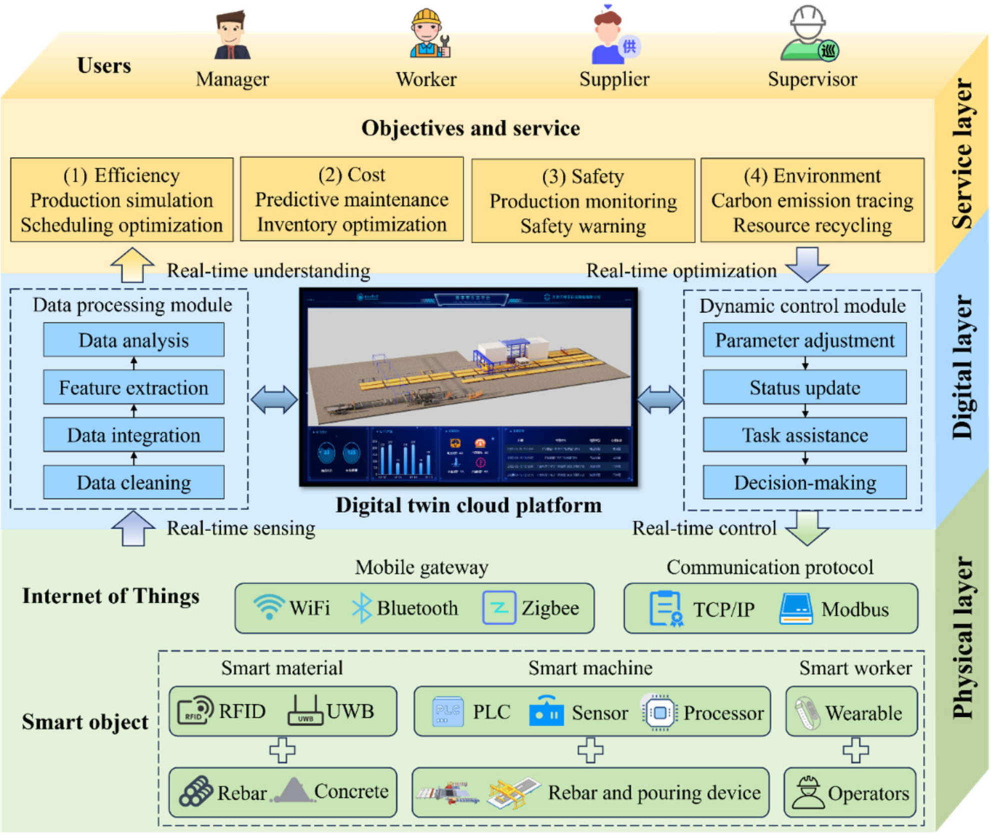


Figure 7. Framework of digital twin cloud platform for prefabricated components developed by the author's team.

From these advancements, digital twin technology emerges as a transformative approach, offering real-time digital representations of construction activities. This technology not only enables more accurate monitoring and management but also facilitates the integration of IoT and advanced algorithms for intelligent decision-making in assembly operations [112]. The endeavors of Zhao *et al*. [113] and Jiang *et al*. [114] in leveraging digital twins for lifting management and modular construction, respectively, underscore the potential of digital twins to significantly enhance the efficiency, safety, and precision of the assembly process. Additionally, Figure 7 depicts the framework of a digital twin cloud platform for prefabricated components developed by the author's team.

In summary, the evolution of assembly technologies in prefabricated construction is characterized by a growing amalgamation of digital and robotic technologies, collectively contributing to enhanced efficiency, accuracy, and safety in construction practices.

3.4. Intelligent operation and maintenance methods

The efficient operation and maintenance of prefabricated components rely on robust supply-chain management, ensuring the seamless flow of materials throughout the entire lifecycle. Wang *et al*. developed a system dynamics model to explore the effectiveness of low-carbon practices in the prefabricated component supply chain [59]. Wang *et al*. contributed a blockchain-based system, revolutionizing information management in supply chains for better transparency and control [115]. Similarly, Du *et al*. developed a decision-support framework using ontology and multi-agent systems, addressing resource distribution and information-sharing challenges to enhance collaborative decision-making [116]. In addition, Zhang and Yu introduced a multi-objective optimization approach that effectively balances cost and flexibility [117]. This method is crucial for enhancing the resilience of supply chains against disruptions. The role of RFID technology, as highlighted by Du *et al*. [118], Naranje and Swarnalatha [119], and Demiralp *et al*. [120], is instrumental in advancing supply-chain tracking and efficiency, moving toward a more streamlined, zero-inventory supply system.

In tandem with advancements in supply-chain management, there is also a burgeoning interest in carbon emission-related research using life cycle assessment (LCA), as seen in Table 4.

Table 4. Carbon emission-related research by using LCA in the operations and maintenance stages.

Research subject	Research content	Literature
Stairs product	Establish carbon-emission calculation model, including production, transportation, and construction substages	Li *et al*. [121]
Prefabricated concrete composite slabs and cast-in-place floor slabs	Establish the carbon-emission calculation model in the production and construction stages	Xu *et al*. [122]
Cement production and prefabricated-component manufacturing	Analyze the environmental effects and optimization potential of prefabricated components	Cheng *et al*. [123]

Table 4. *Cont.*

Research subject	Research content	Literature
Prefabricated exterior walls, balconies, and stairs	Develop a multi-information model that combines BIM and GIS with a LCA approach to quantify greenhouse-gas emissions	Gao *et al*. [124]
Prefabricated components made from three recycling strategies	Investigate the environmental effects of recycled lump concrete and recycled lump/aggregate concrete, along with recycled aggregate concrete, on the production of prefabricated components	Jian *et al*. [125]
Prefabricated concrete interior wall board	Use a process-based method to assess carbon emissions during the prefabrication manufacturing process	Liu *et al*. [126]
Six major prefabricated components	Explore the life-cycle energy use of prefabricated components and investigate its environmental effects on real building projects	Hong *et al*. [127]

Notably, BIM emerges as a pivotal tool, enhancing transparency within the construction value chain and playing a significant role in carbon emission research [128]. The work of Rad *et al*. and Hao *et al*. illustrates the practical applications of integrating BIM with LCA for more accurate economic and carbon-emissions assessments in construction projects [129,130]. Ding *et al*.'s development of a carbon-emission measurement system using BIM further highlights where the bulk of emissions occur-during the material production and construction phases [131]. Moving forward, the focus is likely to shift toward refining these technologies to optimize the design and construction processes, thereby significantly reducing the carbon footprint of building projects. This technological evolution will not only improve environmental outcomes but also enhance the economic viability of construction projects through more precise and efficient resource management.

4. Research gaps and future directions

4.1. Research gaps

The research on intelligent design methods for prefabricated components has focused primarily on design optimization and design data transformation. On the one hand, three aspects need to be considered in design optimization: (1) BIM has gradually become a dominant design tool due to its advantages in visualization, ease of modification, and collaboration. Its adoption also presents challenges, however. Visualization requires higher configurations and a universal design platform, ease of modification needs design-change approval processes to be optimized and appropriate supervision, and collaboration demands solutions to interface issues between various design-software tools and data-security concerns. (2) Linear programming and similar mathematical optimization methods offer targeted solutions for specific design objectives, capable of finding optimal solutions. For complex problems, however, the computational burden may be prohibitive, leading the search for solutions to be infeasible. Heuristic algorithms, as effective design methods, reduce computational complexity and approximate optimal design solutions, but their scalability in complex projects requires enhancement. Deep learning methods further enhance the automation and accuracy of the design process; nevertheless, their demands for significant computational power and expertise in model training may impede their widespread adoption. (3) Existing optimization objectives focus primarily on efficiency and accuracy, aiming to shorten the design cycle of prefabricated building projects and ensure reliable product quality. The current cost of prefabricated components, however, remains significantly higher than that of cast-in-place construction. Therefore, there is a need to reduce the time and personnel costs resulting from frequent design changes and consider the use of recyclable or environmentally friendly materials to reduce carbon-emission costs. On the other hand, two aspects need to be considered regarding design data transformation: (1) The basic requirements for data transformation include reducing errors and improving conversion efficiency, but in-depth research on the cost of transformation and data privacy concerns is lacking. (2) Data formats should be further enhanced for universality and standardization to facilitate seamless data interoperability. This would enable improved integration and exchange of data between different software systems.

Intelligent manufacturing methods encompass four aspects: equipment layout planning, production-scheduling optimization, monitoring, and quality inspection. (1) Firstly, equipment layout planning marks the inception of lean manufacturing and has significant importance. The existing research, however, predominantly focuses on single-story factory layouts. When limited construction space renders it impossible to accommodate all equipment in a single-story layout, the optimization of multi-story factory layouts becomes an area worthy of in-depth exploration. (2) In terms of production-scheduling optimization, the current research primarily concentrates on minimizing completion time, managing delay penalties, and enhancing production efficiency. Nevertheless, there remains insufficient exploration into sustainable environmental requirements and the complexities of dynamic resource constraints. (3) The cost of non-intrusive production monitoring devices remains high, while intrusive monitoring devices still lack usability. The ultimate objective of monitoring data is to provide feedback and adjust the production process, a facet that requires further refinement. (4) Whether based on point metadata or image data, the accuracy of quality inspection meets regulatory requirements. Still, existing DQI methods predominantly focus on the post-production phase, resulting in an inability to rectify defects once detected. This highlights the need to address its inherent lag.

Intelligent construction methods encompass transportation optimization and assembly improvement. (1) Electric vehicles (EVs) could reduce carbon emissions significantly, but the transportation of prefabricated components presents unique challenges that differ from those of passenger transport, necessitating further research to enhance payload capacity and range. Given the size variations in prefabricated components, studying efficient stacking methods to increase transport volume while ensuring safety is crucial. Moreover, optimizing transport routes for prefabricated components should extend beyond merely selecting the shortest path. As these components are prone to damage during transit, it is important to consider measures that also reduce vibrations and impacts. Current practices use GPS and other tracking technologies to monitor the transport status of components, yet these methods often fail to account adequately for sudden events, such as adverse weather conditions or traffic congestion, so discrete and stochastic analysis remains lacking. (2) The assembly phase of prefabricated components relies heavily on automated equipment and effective monitoring mechanisms. While robots and automation systems are increasingly used in the assembly of these components, their integration with other construction management systems is not yet fully realized. Current monitoring methods provide basic oversight regarding efficiency, accuracy, and safety, yet they may not fully address the potential failures or risks associated with the assembly process. Furthermore, as automation in construction becomes more prevalent, the collaboration and division of labor between human workers and robots merit further investigation. More importantly, digital twin technology can precisely monitor the assembly process of prefabricated components, aiding in informed decision-making. Still, the initial investment costs, including expenses for software, hardware, and personnel training, are substantial. Cost–benefit analysis and the development of simplified technological solutions based on digital twins remain in their nascent stages.

The intelligent operation and maintenance method includes two aspects: supply-chain management and full life-cycle assessment. (1) The efficient operation and maintenance of prefabricated components rely on effective supply-chain management, yet challenges persist. While research has explored low-carbon practices and introduced blockchain-based systems for transparency and control, seamless collaboration and information-sharing among stakeholders remain elusive. Decision-support frameworks address resource distribution challenges but need refinement. Multi-objective optimization helps balance cost and flexibility, but comprehensive strategies are needed to ensure supply-chain resilience. RFID technology aids tracking and efficiency, but its full integration may face technical and logistical hurdles. In summary, while progress has been made in supply-chain management, improving collaboration, transparency, decision-making, and resilience remains crucial. (2) Despite the growing interest in carbon-emission-related research and the promising integration of BIA with LCA, notable shortcomings persist. Firstly, there remains a lack of standardized methodologies for BIM–LCA integration, leading to inconsistencies and uncertainties in the assessment results. Secondly, research remains limited on the scalability and applicability of these methods across different construction projects, necessitating further investigation. Furthermore, while some studies highlight emission hotspots during the material-production and construction phases, we still lack comprehensive solutions for emissions mitigation. Future research should focus on standardization, scalability, and developing robust emissions-mitigation strategies to enhance the effectiveness of carbon-emissions assessments in construction projects.

Based on the comprehensive analysis presented earlier, Figure 8 delineates the key research gaps in the development and application of intelligent methodologies for prefabricated construction.

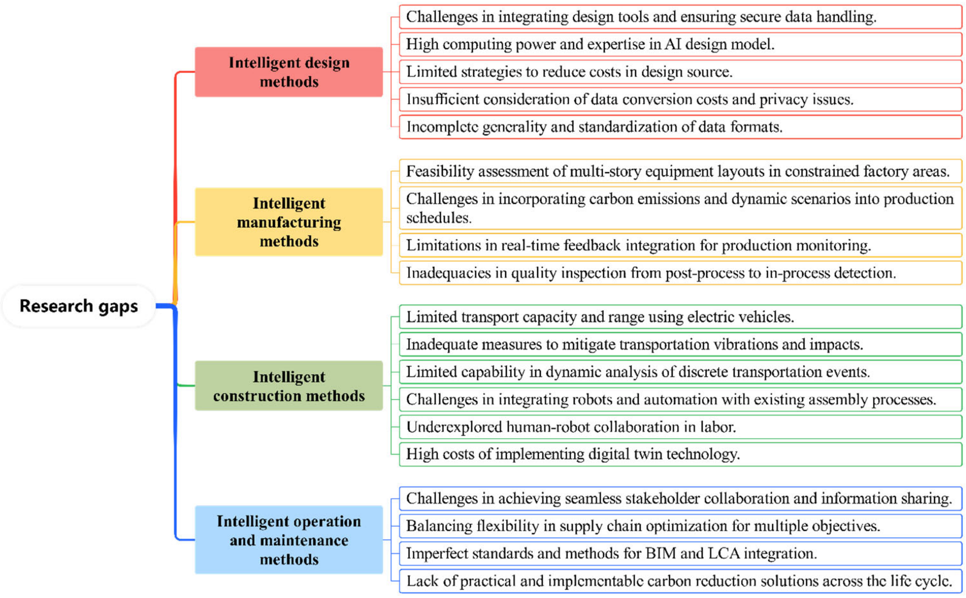


Figure 8. Key research gaps in the development and application of intelligent methodologies for prefabricated construction.

4.2. Future directions

Based on the identified challenges and gaps in current research, Table 5 outlines some future directions for further study.

Table 5. Future directions of intelligent methodologies in precast construction.

Stages	Future directions	
Intelligent design methods	Integration of BIM with emerging technologies	(1) Create an AI-based generative design method to foster innovative and creative solutions. (2) Integrate BIM with virtual reality (VR) and augmented reality (AR) to enhance the design process's efficiency and effectiveness.
	Development of sustainable design methods	(1) Develop green and low-carbon design methods by incorporating LCA principles into the design-optimization process. (2) Explore the use of recyclable materials and eco-friendly construction techniques to reduce the overall carbon footprint.
	Cost-effective design solutions	(1) Explore cost-effective design solutions to minimize design change costs and optimize resource allocation. (2) Standardize the design process to streamline it and reduce overall production costs.
	Standardization and interoperability improvement	(1) Establish common data-exchange standards and protocols that facilitate seamless data transfer between different BIM software tools and platforms. (2) Enhancing data-security measures and address privacy concerns in data-transformation processes.

Table 5. *Cont.*

Stages		**Future directions**
Intelligent manufacturing methods	Multi-story factory layout optimization	(1) Investigate strategies and algorithms for optimizing equipment layout in multi-story factory environments, considering constraints like limited space and vertical integration.
	Sustainability and dynamic resource constraints in production scheduling	(1) Incorporate sustainability considerations and dynamic resource constraints into production-scheduling optimization models. (2) Develop algorithms that can adapt to fluctuating resource availability and environmental objectives, ensuring long-term viability and eco-friendliness in manufacturing operations.
	Cost-effective production monitoring devices	(1) Reduce the cost of non-intrusive devices while enhancing the usability and reliability of intrusive monitoring equipment, thereby enabling comprehensive and accessible production monitoring systems.
	Real-time feedback mechanisms for production monitoring	(1) Develop real-time feedback mechanisms that leverage monitoring data to dynamically adjust production processes. (2) Focus on enhancing the responsiveness and effectiveness of feedback loops to enable proactive adjustments and optimizations.
	In-process quality inspection methods	(1) Explore advanced sensing technologies and data-analytics techniques to enhance the accuracy and efficiency of quality inspection processes. (2) Reduce the reliance on post-production inspections.
Intelligent construction methods	EV-based transportation optimization	(1) Target the development of EVs specifically designed for the transportation of prefabricated components. (2) Increase payload capacity and range to accommodate the unique demands of transporting large and variably sized components. (3) Develop efficient stacking methods to maximize transport volume while ensuring safety.
	Route optimization considering safety	(1) Incorporate advanced algorithms that account for vibrations, impacts, and potential transit damage. (2) Integrate real-time data analytics, including weather forecasts and traffic updates, into routing software to enable dynamic route adjustments that minimize the risk of component damage.
	Advanced monitoring techniques	(1) Integrate various types of automation equipment with construction-management systems. (2) Explore the use of AI and machine learning for real-time monitoring and predictive maintenance to anticipate and prevent equipment failures.
	Human–robot collaboration	(1) Enhance effective collaboration between human workers and robots. (2) Conduct ergonomic and safety standards for human–robot interaction to ensure safe and efficient practices.

Table 5. *Cont.*

Stages		Future directions
Intelligent operation and maintenance methods	Effective supply-chain management	(1) Establish standardized protocols to facilitate seamless collaboration and information-sharing among stakeholders. (2) Refine decision-support frameworks to effectively address resource-distribution challenges. (3) Designed comprehensive strategies to bolster supply-chain resilience against various disruptions. (4) Further integrate RFID technology fully into supply chains.
	Comprehensive life-cycle assessment	(1) Develop standardized methodologies for integrating BIM with LCA to ensure the consistency and reliability of assessment results. (2) Dive deeper into researching the scalability and applicability of BIM–LCA integration across various construction projects. (3) Explore innovative approaches to optimize resource use and minimize carbon emissions throughout the construction life cycle, particularly targeting emissions hotspots during the material-production and construction phases.

5. Conclusion

This article employed a systematic literature review method to comprehensively analyze 114 papers closely related to intelligent construction in the prefabricated industry. These papers were sourced from two prominent academic databases: ScienceDirect and Web of Science. Statistical literature analysis revealed two results. First, papers published from 2020 to the present constitute 72.8% of the total, demonstrating an increase over time and underscoring the growing interest in the subject within the academic community. Second, the analysis identifies the three most used methodologies in this domain: BIM, genetic algorithm, and laser scanning.

The main findings of this review are as follows: (1) This article encompasses the prefabricated construction life cycle: design, manufacturing, construction, and operations and maintenance. It provides readers with a comprehensive understanding of intelligent methodologies in prefabricated construction. This understanding is pivotal in fostering in-depth theoretical research and the exploration of practical application within both the academic and industrial spheres. (2) Gaps in the current research and potential areas for future investigation are identified. Potential directions for future research include generative AI design, dynamic production-scheduling optimization methods, fully automated process quality-inspection methods, long-range transportation methods for EVs, low-cost digital-twin monitoring techniques, and multidimensional, comprehensive life-cycle management systems.

Finally, the following areas should be addressed in future research. Firstly, the research framework established in this article should be refined and enhanced. This includes incorporating additional phases, such as the dismantling and reuse processes. Secondly, the literature related to emerging technologies, such as digital twins and deep learning, should be further enriched, as these technologies are considered efficient catalysts for improving the level of intelligent construction in the prefabricated industry. Lastly, in addition to focusing on the technology itself, it is also essential to consider how various stakeholders in the prefabricated industry can effectively collaborate. This collaboration is key to promoting the intelligent transformation and advancement of the construction industry.

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Conflicts of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' contribution

Xinfei Guo: Conceptualization, Investigation, Methodology, Writing-Original Draft, Visualization. Yimiao Huang: Writing-Review & Editing, Supervision, Resources. Guowei Ma: Writing-Review & Editing, Supervision, Project Administration.

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