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Review article

Digital inspection techniques of modular integrated construction

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ABSTRACT

As a new construction form, modular integrated construction (MiC) can effectively improve the construction quality and productivity, especially for the construction of high-density and high-rise buildings. However, the current MiC quality inspection relies on manual inspection, which is inefficient and unreliable. Systematic research on digital inspection techniques (DITs) is fragmented and unable to fully realize the potential of the MiC industry. This study aims to explore the current state of DIT applications in MiC and to summarize the knowledge in the field through an analysis of 248 relevant literatures. Accordingly, this study combines bibliometric analysis, and a system engineering evaluation approach based on 3D structures (time, knowledge, and logic) to provide an overview of the current state of DIT development. The overview includes the application of DITs from a whole life cycle perspective, the DIT knowledge structure, specific DIT applications, as well as current challenges and future prospects.

1. Introduction

Modular integrated construction (MiC) is a typical prefabricated construction technique with the greatest integration of value-added prefabricated modules [1]. MiC is considered as the most integrated prefabricated construction available [2], and most complete form of offsite construction where 80–90 % of a whole building can be fabricated in a prefabrication factory [3]. Distinct from traditional construction, MiC abandons construction methods that rely on manual work and on-site pouring. It adopts standardized prefabricated component design, factory production, modular construction, and information management to form a complete and organic industrial chain in fabrication, transportation, construction, operation, and maintenance. Through the highly modular and digital adoption and integration of the whole building life cycle, it speeds up construction, reduces labor intensity, and improves project quality and labor efficiency. Therefore, MiC as an innovative solution has become a hot spot for the growth of the construction industry [4].

Despite the clear superiority of MiC, many new quality problems have arisen due to the changes in construction methods, such as dimensional deviations of precast concrete elements (PCEs), surface defects, and positioning deviations of pre-embedded parts. These quality problems can be generally summarized as geometric quality problems (e.g., dimensions, locations, cracks, and missing corners) and non-geometric quality problems (e.g., anchorage, deflection, and bond strength) [5,6] of PCEs during fabrication, transportation,

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construction, operation, and maintenance with actual design mismatch. These quality problems reduce the yield rate of manufacturers, limit the effectiveness of manufacturing line, and disguise the growth of the MiC industry. However, the traditional inspection method relies only on visual inspection by inspectors using simple tools (tape measure, horizontal ruler), manual recording of inspection data, and document analysis. This approach relies heavily on the inspector's limited knowledge and experience, resulting in low inspection efficiency, high cost, and even susceptibility to human error [7]. These new quality deficiencies are primarily attributed to the lack of efficient self-inspection and re-inspection tools for the entire manufacturing process.

With the increasing development of MiC and the need to inspect the quality of a large number of PCEs with a higher degree of complexity, the traditional manual inspection methods can no longer adapt to the current development trend. In this context, additional digital inspection techniques (DITs) have emerged in recent years, such as 3D laser scanning, photogrammetry, image detection, acoustic emission, and infrared detection [8]. However, these studies lack the foundation, evolution, and trend description of DIT knowledge, and the overall research status remains unsystematic and fragmented. Additional studies are addressing MiC quality testing from different perspectives. Therefore, to fill the gaps of the above studies, this study integrates relevant knowledge of DITs with the following objectives: (1) identify mainstream applications of DIT in MiC; (2) propose a knowledge structure for the application process of DIT in the MiC; (3) summarize the current challenges and future research directions of DIT application in MiC.

Taking the applications of DITs in MiC as a perspective, this study provides a comprehensive and systematic analysis and summary of DIT-related publications published from 2012 to 2022 and uses a combination of quantitative and qualitative analysis to review the current research status and predict future research directions. This study also compares the current state of development of the DIT structure of knowledge and mainstream DITs to further stimulate researchers to understand and develop DITs.

2. Research methodology

To ensure the objectivity of the literature assessment and a deeper understanding of the target domain and trends [9], this study used a "mixed methods" approach, including quantitative analysis (bibliometric analysis) and qualitative analysis (systematic evaluation). Based on 11 years of literature from 2012 to 2022, research in the field of DITs was assessed in three steps. Fig. 1 shows the workflow of this study.

2.1. Bibliometric search

- Database: Initial literature search using Web of Science (WoS) and Scopus. The WoS database is recognized as a comprehensive academic information resource database that can scientifically reflect the research level and cover a large number of disciplines. Scopus database has a faster indexing process and up-to-date publications [10].
- Keywords for retrieval：For a more comprehensive search of the literature in the target domain, we use the search string consisting of two parts [11] The first part comprised keywords related to "modular integrated construction" or "precast element" or "off-site manufact*" or "off-site construction" or "industrial construction" or "industrialised building*" or "prefabricat*" or "precast concrete." The second part comprised "quality*".

The asterisk (*) above indicates a wildcard character.

- Quality of literature: Given that some conference papers were retrieved from the Scopus database, abstracts and keywords were manually reviewed for relevance to the MiC industry and DITs to guarantee the level of the selected papers.
- Timespan: Owing to the small amount of literature published in the target domain prior to 2012, the literature published from 2012 to 2022 was evaluated and reviewed to conduct a sustainable systematic review analysis.

Finally, a total of 248 papers were selected as the material for this study, and Fig. 2 shows the detailed process.

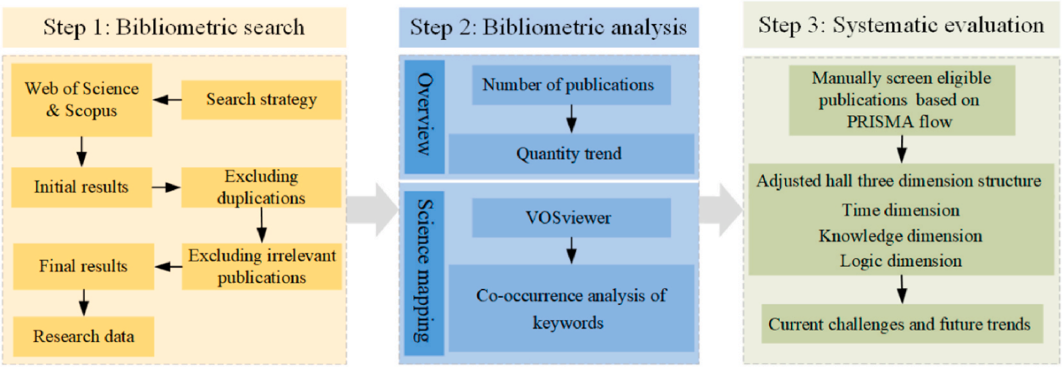

Fig. 1. Research framework of this study.

2.2. Bibliometric analysis

Bibliometric analysis is a method based on collecting large amounts of academic data to assess the impact of research and citation processes in a target field and to map the knowledge framework of the research field and its evolution [12]. This study uses scientific cartographic analysis and visualization of bibliometric networks, the aim is to obtain valid information by summarizing the mainstream topics of DIT applications, visualizing important categories and trends, and using a large sample of literature [13].

2.3. Systematic evaluation

Systematic evaluation is the final step of the research line. This study is based on hall 3-dimensional structure (H3DS) and extends its application [14,15]. Previous studies have used a three-dimensional structure of time, knowledge, and logical dimensions to describe the interactions of the content of each dimension, which is very helpful for systematically understanding the application scope, knowledge base, and operation logic of DITs. Based on the study by Liao et al. [16] and the purpose of this study, the fabrication, transportation, construction, and operation and maintenance phases of DIT application are used as the time dimension, the knowledge base that drives the application of DITs is used as the knowledge dimension, and the process of applying DITs to solve problems is used as the logic dimension. On the basis of this information, the process of the role of DITs is systematically analyzed, the research in this field is discussed, the challenges of current research in this field are identified.

3. Findings of bibliometric analysis

This section gives an analysis of the literature, including general research trends in the application of DIT in each process of the MiC life cycle, mainstream topics, and the current status of the application of DIT in each process.

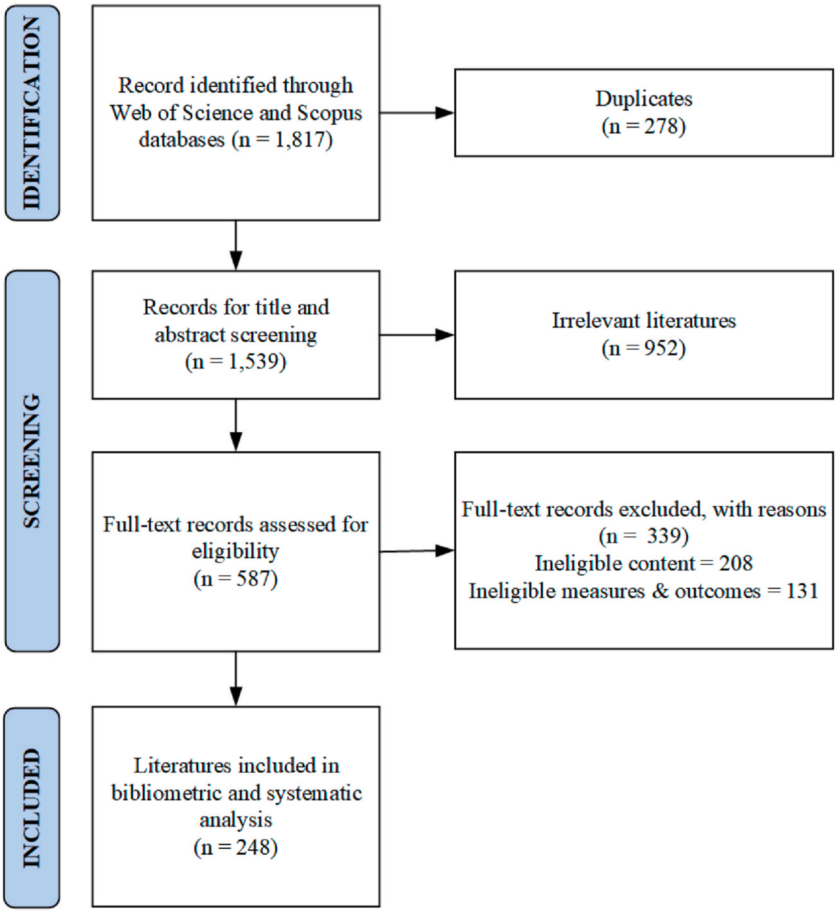

Fig. 2. Literature screening process.

3.1. Overall status of the literature samples

Fig. 3 depicts the publication dates of the 248 retrieved literatures, which show the general research trend of the applications of DITs in each phase of the MiC life cycle during the last 11 years. The year 2012 only has 8 papers published, which is a small number. For the years from 2013 to 2018, 10–20 papers were published each year, which can by now show the stable development of DIT research during this period, despite the fluctuation in the number of papers published each year. From 2019 to 2022, the number of papers published per year is significantly higher than those published before 2019 due to the rapid development of computer technology accompanied by better solutions for MiC quality detection. This general trend indicates that research on DITs has received increasing attention from researchers in recent years. The results of Wang et al. [8] also proved this assumption.

The number of publications on fabrication and construction phases is high and the overall trend is increasing, indicating that these two phases are the focus of quality control. As for transportation phase, the research is limited by the trucking method, and the current research focuses on the use of GPS, RFID and other technologies to track the location and quality information of the components [17, 18]. Operation and maintenance phase is the longest phase in the building life cycle, and the research on this phase is gradually receiving attention from researchers in recent years. MiC needs a more efficient way to monitor the health of the structure, so that the advantages of modular design can be exploited to a greater extent.

3.2. Co-occurrence analysis of keywords

In the Vosviewer composite network diagram, the node and font sizes correspond to the number of literatures, and the thickness and distance of the links between nodes indicate the degree of contact relationship, dividing closely related nodes into clusters using different colors. Two main indicators were used for the analysis in this study. The first indicator is the number of occurrences, which represents the output of the target research; a higher value of this indicator indicates a greater contribution of the publication to the target field and likewise a greater node in the composite network diagram. The second indicator is Avg. norm. citations, which indicate the degree of impact [19]; the higher the value of this indicator, the greater the impact on the target domain, and the table content is ranked according to the magnitude of this value. The above two indicators do not affect each other, that is, journals with more published literature do not necessarily obtain a higher number of citations [20].

Keywords are a high level summary of the research content of the paper and can provide an accurate theme of the research in the target domain [21]. The minimum number of keyword occurrences was set to 4, and 63 of the 1544 keywords that met the condition threshold were further analyzed. For a clearer analysis of keywords, use “prefabricated construction” for the keywords related to “modular integrated construction” in Section 2.1, as shown in Table 1 and Fig. 4. According to the average normal citations listed in Table 1, the keywords with higher values include progress measurement, object recognition, reconstruction, and registration. This finding indicates that influential studies focus on PCE manufacturing and construction schedule management [22], improvement of detection capability of DITs [23], and exploring the application of emerging digital technologies. The average publication year shows the most recent time a given keyword has been studied in the DIT field. For example, the more traditional keywords included computer aided drafting (CAD), reconstruction, and identification. By contrast, Registration, Deep learning, and machine learning have become the focus of academic attention in recent years.

In this study, four clusters of different colors (see Fig. 4) were obtained using the VOSviewer co-occurrence analysis method,

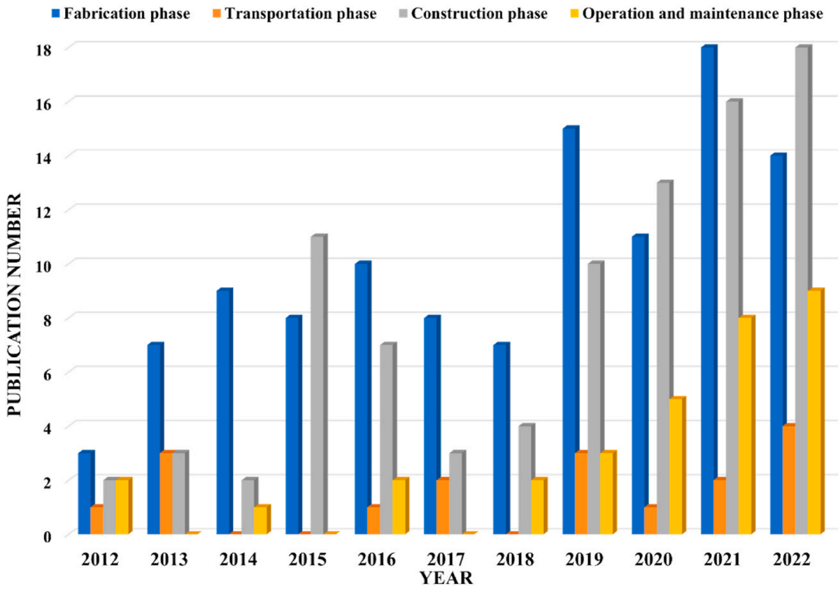

Fig. 3. Yearly DIT-related publications from 2012 to 2022.

Table 1
Quantitative analysis of keywords in DIT research.

Keywords	Occurrences	Avg. citations	Avg. norm. citations	Avg. pub. year
Progress measurement	5	99.40	4.96	2018
Object recognition	4	77.25	3.57	2018
Reconstruction	11	98.82	3.43	2017
Registration	5	27.00	3.31	2022
Tracking	7	56.71	3.16	2018
3D reconstruction	5	43.80	2.76	2021
Deep learning	4	21.00	2.22	2020
Visualization	5	78.20	2.20	2018
Cad	4	99.25	2.17	2016
Management	6	70.17	2.11	2018
Point cloud	22	27.55	2.04	2020
Automation	5	33.40	2.01	2022
BIM	42	32.26	1.87	2018
IOT	4	25.25	1.81	2019
Identification	5	62.40	1.77	2017
3D laser scanning	40	36.97	1.72	2021
Segmentation	4	65.25	1.69	2022
Buildings	11	18.27	1.66	2018
Photogrammetry	37	33.41	1.62	2017
Digital twin	4	3.50	1.51	2021
Safety	7	21.57	1.38	2018
Imaging	4	3.75	1.36	2019
Machine learning	4	3.75	1.36	2020
Damage detection	18	14.56	1.15	2019
Machine vision	5	18.40	1.14	2018

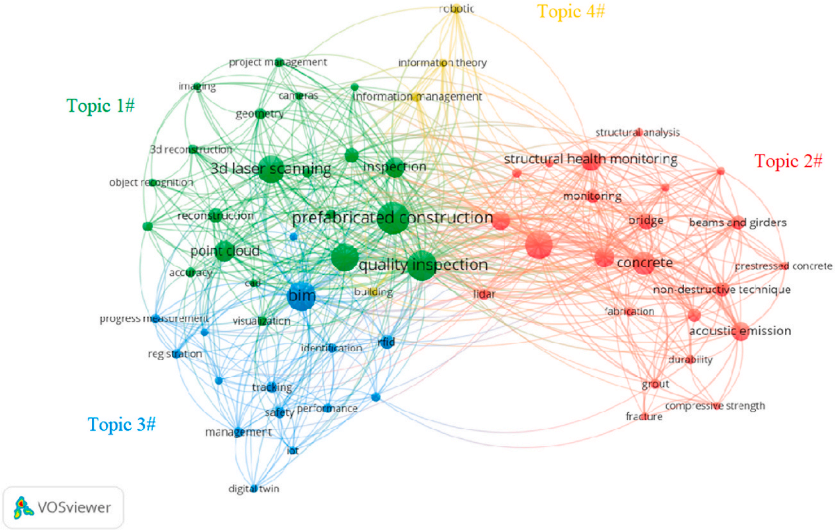

Fig. 4. Mapping of keywords in the DIT domain (2012–2022).

representing four main research themes in the field of DITs (see Table 1). After manually checking the keywords in each cluster to create clustering themes, on which the four themes are labeled, including detection and evaluation of geometric quality, detection and evaluation of non-geometric quality, schedule management in the context of multi-technology integration, and data-driven MiC information management, Section 5.3 provides an in-depth discussion of each theme to summarize the application of DITs.

3.3. DIT applications in the lifecycle phases of MiC

The different lifecycle phases of DIT applications as presented in this study. DITs provide the opportunity to deal with quality problems more efficiently and reliably [24]. This section provides an in-depth analysis and summary of the current status of the application of DITs in the field of quality inspection and innovatively takes the four stages of manufacturing, transportation, construction, and operation and maintenance as the entry point to analyze in detail the application of DITs in each process of each stage and to explore the processes where DITs can be applied. Summary of the application status of DITs at each phase, as shown in Fig. 5.

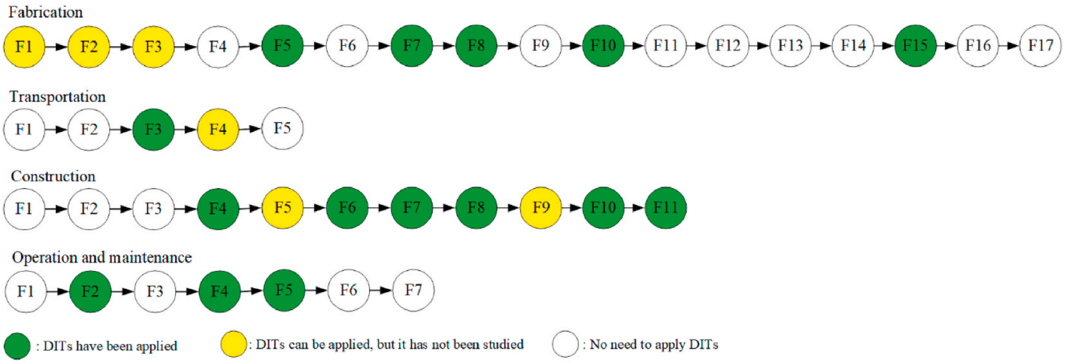

Fig. 5. Summary of the application status of DITs at each phase.

3.3.1. *Applications in the fabrication phase*

In this study, the manufacturing process of precast concrete laminated panels is used as an example; after analyzing the selected literature, the manufacturing is divided into 17 production processes [25]. As can be seen in Table 2, DITs are not fully applied to every process, such as F4, F6, F9, F11, F12, F13, F14, F16, and F17, which is understandable because not every process requires quality inspection. For F1, F2, and F3, these processes can be applied to DITs, but no research has been done yet. For F1, the surface of the mold table is inspected to avoid defects and poor appearance of the PCE surface due to uncleanliness. For F2, the mold positioning is inspected to avoid errors in the mold assembly dimensions. For F3, the installed mold is inspected to avoid deviations in the PCE dimensions due to mold deformation and poor connections. For F8, two major quality defects exist in this process. The first is the pounding time which is too long, resulting in concrete layering and segregation; in addition, the time is too short or not in place, resulting in honeycomb cavities. The second is the unreasonable placement of the vibrating rod, and the concrete thrust leads to the position of the pre-embedded part deviation.

Table 2
Current status of DIT applications of precast concrete laminated panel fabricating process.

Process	No.	Current Status	Target Problem	Used DITs	Relevant Literature
Mold table cleaning	F1	○			
Mold positioning	F2	○			
Mold Installation	F3	○			
Spray mold release agent	F4	×			
Pre-embedded installation	F5	✓	Location, dimensions	3D laser scanning	[26–29]
			Location, dimensions	Photogrammetry	[26]
Rebar processing	F6	×			
Rebar tying	F7	✓	Location	3D laser scanning	[27,30]
			Dimensions	3D laser scanning	[7,30]
Concrete pouring	F8	✓	Grout density	Wireless sensor	[31]
Concrete brushed	F9	×			
Curing	F10	✓	Surface state	Photogrammetry & true color camera	[32]
			Thermal performance	Wireless sensor	[33]
			Thermal performance	Infrared detection	[34,35]
Mold removal	F11	×			
Finished product lifting	F12	×			
Finished product water testing	F13	×			
Finished product rinsing	F14	×			
Finished product inspection	F15	✓	Compressive strength	Photogrammetry	[36]
			Curvature	Photogrammetry	[37]
			Surface defects	Photogrammetry	[38–42]
			Surface defects	3D laser scanning	[4,43–55]
			Surface defects	Infrared detection	[34,35]
			Dimensions	3D laser scanning	[51–53,55–66]
			Injury location	Acoustic emission	[6,67–76]
			Shear stress	Acoustic emission	[77]
			Strength, stiffness	Ultrasound	[5]
			Rebar position, stress	Ground penetrating radar	[78]
			Integrity	Camera	[54,79]
			Internal load	Wireless sensor	[80]
Sanding and repair	F16	×			
Finished product shipment	F17	×			

Note: Check (✓) indicates that DITs are used in this process. Check (×) indicates that DITs application are not required in this process. Check (○) indicates that DITs can be applied to DITs, but no research has been done yet.

For F5, F7, F8, F10, and F15, these processes have been studied with the application of DITs. For F5, the installation process of the pre-embedded parts is inspected to ensure the accurate positioning and correct dimensions of prefabricated mechanical, electrical, and piping (MEP) modules [26,28].

For F7, the classification of rebar is unclear, leading to low efficiency. Kim et al. [30] proposed a method for automatic classification of rebar diameters and accurate estimation of rebar spacing based on ground laser scanning using machine learning algorithms.

For F8, Uotila et al. [31] obtained the load and its vibration data during concrete placement by pre-built wireless strain sensors and then determined the compactness of the concrete placement. For F10, the indicators with a large impact on quality in this process are temperature and the surface condition of PCEs. Newell et al. [33] investigated the thermal properties of concrete by collecting the confinement coefficients and in situ thermal expansion confinement coefficients of concrete by pre-embedding embedded sensors in PCEs. Infrared thermography is also used to monitor the concrete curing temperature and thus determine the maturity of the concrete [34]. For the surface condition at the time of maintenance, the main indicators are the crack pattern, displacement, and strain field of PCEs [32]. F15 is a key step in the dit application and includes the inspection of the dimensions, surface quality, and internal quality of the PCEs. To prevent failures during construction, checking that the relevant geometric and non-geometric quality indicators meet the specified tolerances during this process has become increasingly important.

3.3.2. Applications in the transportation phase

After analyzing the existing studies, the transportation phase was divided into five processes as shown in Table 3. The transportation phase, while covered briefly in the literature concerning the application of DITs, has profound significance given that it is an important part of MiC projects that distinguishes them from traditional construction projects. From Table 3, T1, T2, and T5 can be seen to not require quality inspection. T4 can apply DITs, but no relevant studies exist. T4 can inspect PCEs stacked on site to avoid quality problems such as damage and deformation due to stacking. T3 has been studied for DIT applications. For T3, Hanteh et al. [81] monitored the areas of tensile stress during transport of PCEs through acoustic emission and then identified and located the cracks.

3.3.3. Applications in the construction phase

Majority of studies applying DITs to the construction phase of a MiC project have been focused on assessing the structural integrity of the object. This study takes the assembly process of prefabricated modules as an example. The construction phase is divided into 10 processes as shown in Table 4. It can be seen that the C1, C2, and C3 processes do not require quality inspection. The C8 process can apply DITs, but relevant studies are still lacking. The C4, C5, C6, C7, C9, and C10 processes have been studied with the application of DITs. For C4, Jiang et al. [82] calculated the distance between different steel bars by estimating the kernel density of the point cloud. For C5, the installation of the module in place at the construction site is the ultimate accurate drop process, requiring real-time communication between multiple construction personnel and the crane operator to adjust the module drop position. Zhao et al. [83] processed point clouds acquired through 3D laser scanning and checked whether the installation meets the quality requirements for geometric parameters such as angles and distances. For C6, high-strength bolting or welding technology is used to connect modules as a whole [4]. For C7, the geometric quality of prefabricated MEP modules is inspected to ensure accurate positioning and correct sizing of MEP components during installation. For C9, sleeve grouting is widely used in the connection of components to form key nodes, and the tightness of grouted sleeve connections plays a decisive role in the safety of the structure, especially in its seismic capacity. For C10, Hu et al. [84] tested the lateral displacement and deformation of the assembled pit structure and improved the theoretical basis for the development of underground structures.

3.3.4. Applications in the operation and maintenance phase

In this study, the operation and maintenance phase is divided into seven processes as shown in Table 5. The O1, O3, O6, and O7 processes do not require quality inspection. The O2, O4, and O5 processes have been studied for the application of DITs. The O2 process is the main study of the application of DITs in the operation and maintenance phase, focusing on structural performance, such as displacement [103], vibration [104], deformation [105], and acceleration at points of interest on the structure [106]. This process is mainly to establish the information base and maintenance plan of PCEs to manage their operational status and cover the whole process from maintenance application to completion acceptance in case of failure. O4 focuses on collecting and analyzing quality indicators and energy consumption [33] to provide energy saving and project operation optimization operation basis to improve the operational efficiency of the project and contribute to the predictive maintenance of the project. O5 focuses on various analysis and management needs in the space aspect, such as in the daily inspection and maintenance process, to quickly query the structural deformation status, numbering of PCEs [107], the floor, room number.

Table 3
Current status of DIT applications of the transportation phase.

Process	No.	Current Status	Target Problem	Used DITs	Relevant Literature
Program Preparation	T1	×			
Loading	T2	×			
Distribution	T3	✓	Injury location	Acoustic emission	[81,17]
			Location	Wireless sensor	[18]
Unloading site stacking	T4	○			
Vehicle return	T5	×			

Table 4
Current status of DIT applications in prefabricated modular assembly construction process.

Process	No.	Current Status	Target Problem	Used DITs	Relevant Literature
Measuring and placing lines	C1	×			
Gasket leveling	C2	×			
Mortar belt laying	C3	×			
Pre-rebar correction	C4	✓	Rebar location	3D laser scanning	[82]
Modular location	C5	✓	Location	3D laser scanning	[2,23,85–87]
			Location	Camera	[88]
Module Node Connection	C6	✓	Cracks	Photogrammetry	[89,90]
			Cracks	Acoustic emission	[76,91]
			Cracks	3D laser scanning	[4,92]
Pre-embedded installation	C7	✓	Surface Integrity	3D laser scanning	[93,94]
			Parts integrity	Photogrammetry	[95]
			Parts integrity	Fiber optic sensor	[96]
Rebar tying	C8	○			
Concrete Pouring	C9	✓	Grout density	Acoustic emission	[97–99]
			Grout density	Impact echo method	[100]
			Grout density	Ultrasound	[101]
			Grout density	Wireless sensor	[102]
Curing	C10	✓	Deformation	Wireless sensor	[84]

Table 5
Current status of DIT applications of the operation and maintenance phase.

Process	No.	Current Status	Target Problem	Used DITs	Relevant Literature
Data Collection	O1	×			
Structural Health Management	O2	✓	Cracks, deformation	Photogrammetry	[108,106]
			Cracks, deformation	Wireless sensor	[109,105]
			Cracks, deformation, location	True color camera	[110,104]
			Cracks	Infrared detection	[111]
Equipment Management	O3	×			
Energy consumption management	O4	✓	Energy efficiency		[33]
Space Management	O5	✓	Location	3D laser scanning	[55,107,112]
Asset Management	O6	×			
Environmental Management	O7	×			

4. Systematic evaluation and results

In this paper, based on an in-depth analysis of the selected literature, the authors summarize the current mainstream topics of DIT research (section 3.2), analyze the current status of DIT application in MiC quality inspection (section 3.3), and then conduct a systematic evaluation (qualitative analysis) of the current status of DIT application using the optimized H3DS. The H3DS of this study consists of three dimensions: time, knowledge, and logic, as shown in Fig. 7.

4.1. Identified DITs

Table 6 and Fig. 6 show the results of the identification of individual DITs. A total of 10 DITs were recorded, and the number of times is the frequency of occurrence of DITs as keywords. Among them, 3D laser scanning, photogrammetry, and acoustic emission received the most attention, with frequencies of 40, 37, and 30, respectively. Other types of sensors were broadly grouped into wireless

Table 6
Number of occurrences of DITs as keywords.

DITs	Occurrences
3D laser scanning	40
Photogrammetry	37
Camera	7
Acoustic emission	30
Impact echo method	5
Ultrasound	9
Ground penetrating radar	8
Infrared detection	10
Wireless sensor	8
Fiber optic sensor	1

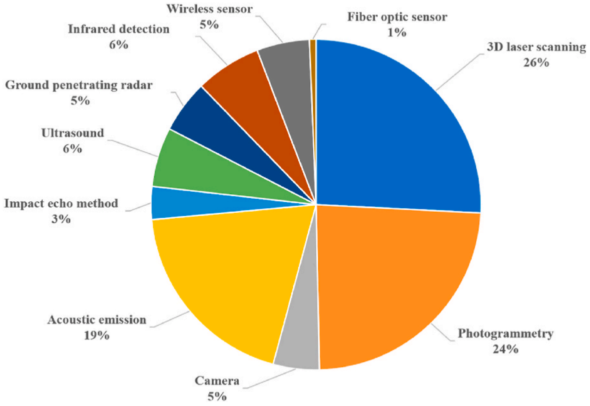

Fig. 6. Distribution of DITs in reviewed papers.

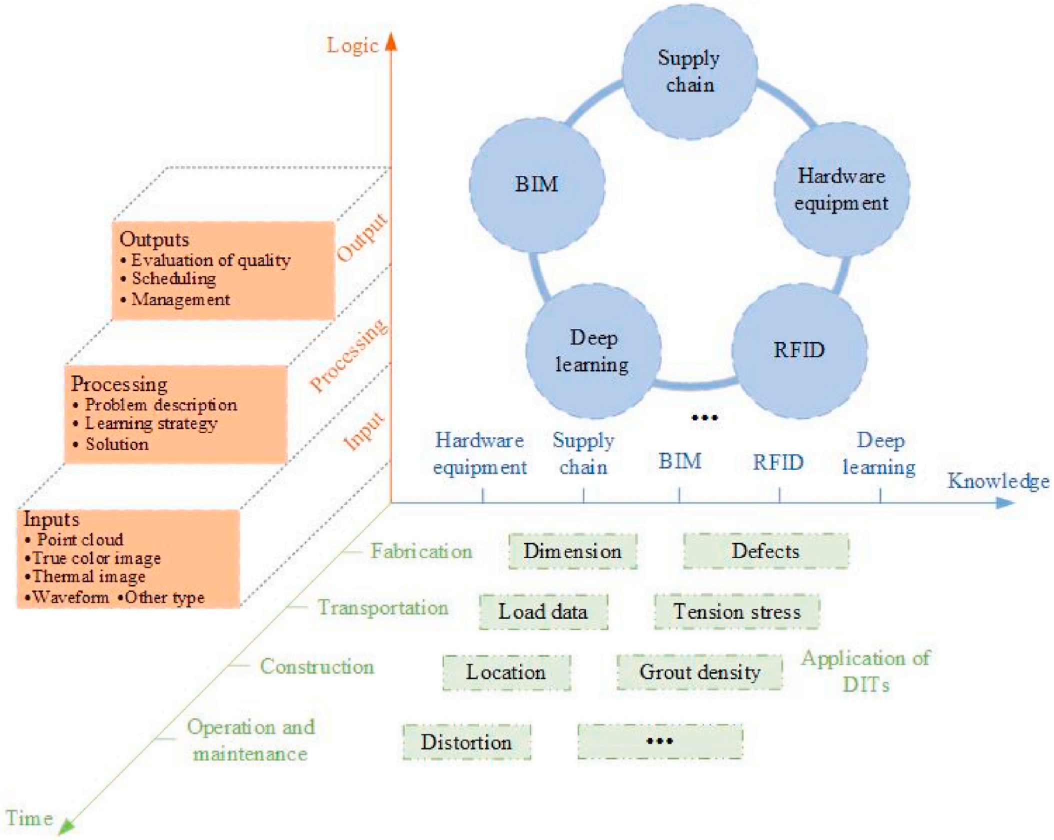

Fig. 7. H3DS of system evaluation.

sensor and optical fiber sensor with frequencies of 8 and 1, respectively.

4.2. *Systematic analysis of DITs*

This study uses a three-dimensional structure consisting of knowledge, logic and temporal dimensions in order to gain a more in-depth and comprehensive understanding of the whole process of application of DITs, as shown in Fig. 7.

4.2.1. *Time dimension*

The time dimension under H3DS is to sort out the sequence of a series of activities. In this dimension, this study divides the MiC project into four phases according to its life cycle: fabrication, transportation, construction, operation, and maintenance phases. Section 3.3 analyzes the specific application of DITs in these four phases. The application of DITs is an information flow process [113]. Although no studies exist on the application of DITs in the bidding and design phases, these two phases also have a very important role in building the MiC quality inspection framework [61]. For example, the production capacity of PCE suppliers is evaluated during the bidding phase. The selection and design of more suitable PCEs are a chieved during the design phase.

4.2.2. Knowledge dimension

The content of the knowledge dimension refers to the knowledge base that constitutes the application knowledge of DITs. The application of DITs in the MiC industry is a repository of integrated multi-class knowledge that integrates building information modeling (BIM), supply chain, radio frequency identification (RFID), deep learning, and so on. In this dimension, this study focuses on the functions of various types of knowledge and the current state of research on integrating the use to better drive the goals of DITs. First, hardware equipment is crucial to the application of DITs, and the development of hardware equipment allows for the removal of manual detection. Further improvement of the detection efficiency of PCEs also relies on the further development of the performance of hardware equipment.

After investigating the literature, the authors found four typical applications of BIM derived from the field of DITs, which enrich the content of BIM while laying the foundation for the study of DITs. The four types of BIM applications are as-is-BIM, scan-vs-BIM, scan-to-BIM, and cloud-BIM, as shown in Fig. 8.

As-is-BIM builds BIM from the process of acquiring point cloud data. Wang et al. [114] proposed a method for automatically extracting building geometries from unorganized point clouds. The acquired raw data undergo cleaning, boundary detection, and component type classification so that the components are identified as individual objects and visualized as polygons. The proposed method indicates that it can simplify and speed up the creation of prefabricated components. In Scan-vs-BIM, based on geometric alignment and comparison of reconstructed 3D models with as-designed BIM models, prefabricated elements, and MEP components can be effectively identified [52,93,115,116]. In Scan-to-BIM, 3D laser scanning has been leveraged to capture the accurate as-is conditions of prefabricated components or buildings and create as-is BIM models of them. In Cloud-BIM, BIM is combined with cloud technology to facilitate automatic and efficient transfer, storage, and access to PCE quality inspection data [83]. As shown in Fig. 7, all the pieces of knowledge are interconnected, illustrating that all the knowledge involved in the application of DITs is mutually supportable. The latter holds because integrating all the knowledge works together to better realize the functions of DITs.

4.2.3. Logic dimension

The logic dimension of this study refers to the three-step problem-solving process of DITs, which includes input, processing, and output (see Fig. 7). The first step is input. A difference exists between different DITs in terms of data type input (see section 5.2). The second step is processing. Depending on the input data, the appropriate method or model is chosen to obtain the results. How to obtain the desired results is a key element of each type of DIT study. For example, in the processing of point cloud, after obtaining the initial point cloud, how to align it, how to reconstruct the geometric surface, and how to identify the semantic information and finally integrate it to generate a 3D model to provide data support for subsequent specific applications are the core issues of point cloud data processing technology [93,117,118]. The last step is output. The output contains information that can determine the quality status of PCEs and can be further used for the production scheduling of PCEs [119] and construction schedule management [120]. BIM and digital twin can be used as integrated models to achieve synergy between parties. BIM has produced standards such as industry foundation classes (IFC), identity management (IDM), and international framework for dictionaries (IFD) to address information exchange and sharing to achieve horizontal multi-professional integration and vertical process integration [121].

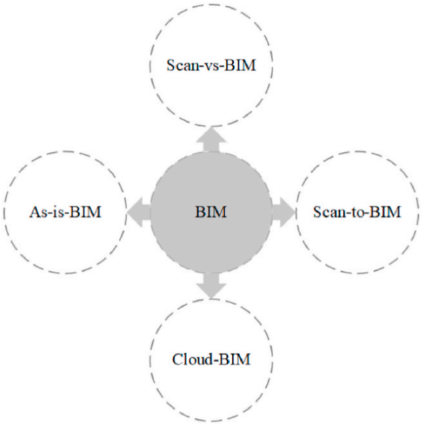

Fig. 8. Driving effects of BIM on DITs.

5. Knowledge synthesis in DIT applications

Informatics is built as a hierarchy [122]. This study adapts on this basis, and the proposed knowledge structure (see Fig. 9) is a knowledge representation [16], which reveals the knowledge base, technology classification, and application topics of DIT application in the field of quality inspection in MiC industry from bottom to top.

5.1. *Knowledge basis*

The knowledge base consists of the keywords identified in the previous section. As shown in Fig. 9, the method basis includes multidisciplinary knowledge, such as deep learning, machine vision, remote sensing, structural analysis, and information theory. The technology basis includes multidisciplinary knowledge, such as BIM, RFID, IOT, supply chain, big data, and digital twin. The content of keywords reflects the composition of DIT knowledge as a whole, including hardware equipment, integration of multiple technologies, problem-solving strategies, and the algorithm of the solution. Prior to applying DITs, the knowledge mentioned above are essential to better understand the problem-solving process of DITs [123]. In addition, the complementarity between different knowledge is the cornerstone of DIT development and application.

5.2. *Categorization of DITs*

This study classifies specific technologies into five categories based on different types of quality inspection data obtained, including point cloud-based DITs, true color image-based DITs, waveform-based DITs, thermal image-based DITs, and other type-based DITs, based on the definitions of DITs in this study.

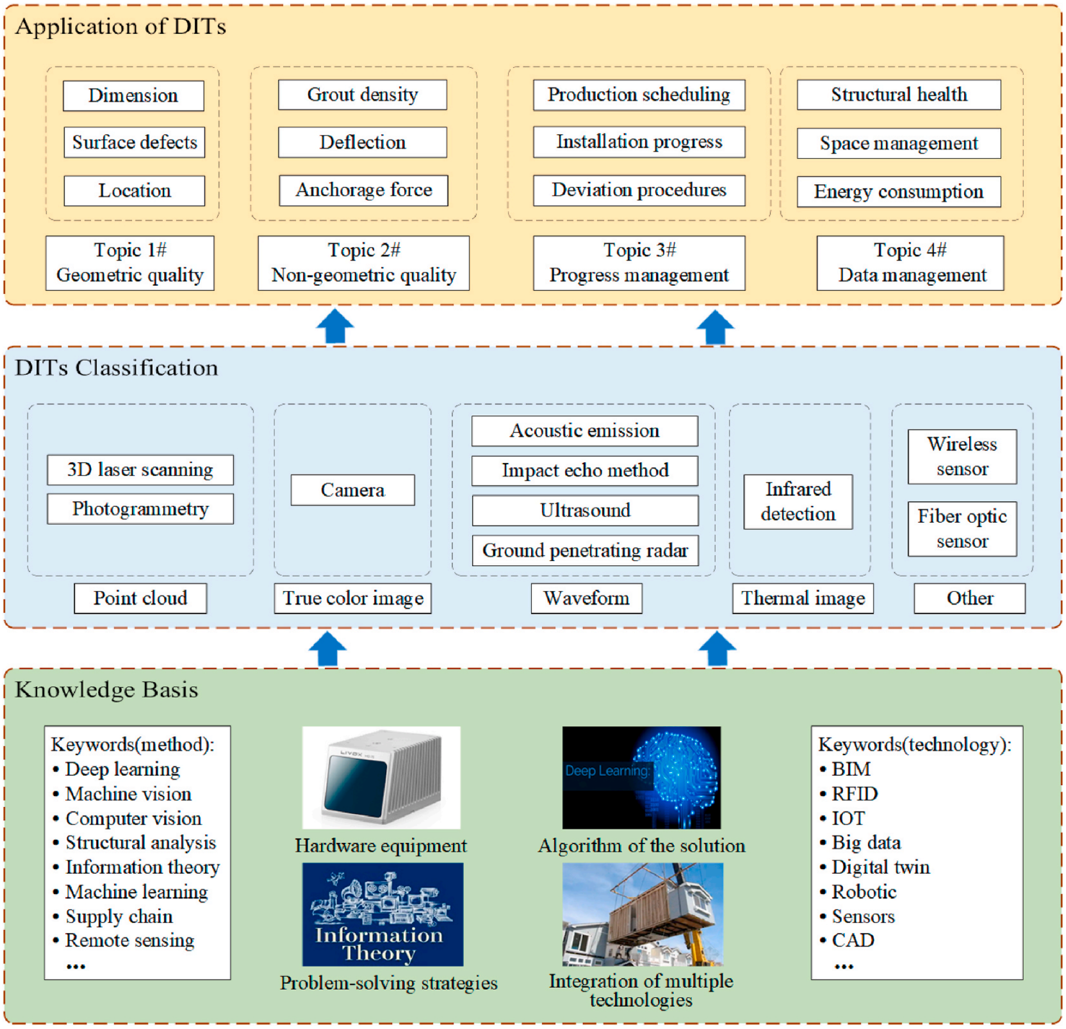

Fig. 9. Knowledge structure of DITs applied in MiC industry.

(1) Point cloud-based DITs

The point cloud-based DITs include 3D laser scanning, photogrammetry, stereo camera, and video measurement. The high-precision acquisition of point cloud and the extraction and utilization of semantic information are the main contents of current point cloud research. 3D laser scanning and photogrammetry are typical representatives of such DITs [119,124] Studies have been conducted to review the specific processes of the two types of DITs [120,125,126]. As can be seen from the system evaluation, point cloud-based DITs have difficulties in semantic information extraction and precise and complex geometric semantic analysis of point cloud data, resulting in the failure of point cloud-based DITs in many complex quality inspection problems when faced with an explosion of data and increased complexity in the MiC industry.

(2) True color image-based DITs

The true color image-based DITs is to take images using a true color camera. The study of segmentation methods for crack images with different resolutions was previously a hot topic [54], but the results are unsatisfactory [127]. Along with the emergence of new DITs, research on the quality detection of true color images has focused more on the coupling with other DITs. The 4D information provided by true color data can enhance the visual detection of damage types, such as corrosion, cracks, and other surface defects, and thus substantially increase the speed of detection. Achieving this process is often difficult with laser scanners [54]. In addition, the true color image-based DITs are faster and suitable for large-scale data acquisition from different locations. However, meeting the requirements of accuracy of PCEs is difficult, and the latter is more often used for construction progress monitoring. In particular, neural networks, genetic algorithms, and computer vision have received much attention from researchers [22]. Combining the best characteristics of point cloud and true color images and expanding the data standard of point clouds to achieve the detection and quantification of surface damage of PCEs are directions for future research.

(3) Waveform-based DITs

The waveform-based DITs include acoustic emission, ultrasound, impact echo method, and ground-penetrating radar. Acoustic emission is the use of sound waves generated by a passive detection material. The impact echo method uses acoustic waves provided by an external device and then receives the echoes using a transducer. Ultrasound is the active emission of ultrasound waves and then receiving the echoes.

Given that the three sources of acoustic waves are different, the three are summarized separately in this study. Ground-penetrating radar detection is done by emitting millimeter waves [78].

The acoustic waves for acoustic emission detection come from the object under test itself without the need for external equipment to provide them, and the elastic deformation and damage of the material are all sources of emission. The impact echo method is more suitable for the internal defect detection of PCEs such as precast beams, slabs, and walls. Additionally, the detection of PCEs with complex structures is limited [75]. Ultrasound can only qualitatively analyze whether a defect exists but cannot provide the size of the defect [98]. In summary waveform-based DITs determine quality issues by detecting waveforms and do not generate reconstructed models.

(4) Thermal image-based DITs

The thermal image-based DITs is the detection of external and internal defects of PCEs using an infrared thermal image detector. By receiving the infrared signal radiated by the concrete, the heat distribution in the heat spectrum image is derived, and the infrared heat radiation of the non-normal body is significantly different from that of the normal concrete PCEs, which is used to detect the presence of abnormal PCEs [35]. The welding state, defect size, defect thickness, irradiation temperature and angle [34], and detection angle, all have an impact on the accuracy of infrared thermography detection results, which also limits the application of such DITs [111].

(5) Other type-based DITs

The other type-based DITs include wireless sensor, fiber optic sensor, and so on. Such DITs are mainly pre-embedded sensor methods. The detection elements are pre-placed at the target location, and the required data are continuously collected by the detection equipment and the detection elements to qualitatively evaluate the quality problems. Yao et al. [102] used sensing technology to collect quality data, such as grout compactness and mechanical properties within prefabricated uniform layer sleeves, to build a quality control model; they then applied a real-time early warning system to the quality control model of the MiC nodes. However, certain limitations exist, such as the inability to detect defects in other locations [33].

5.3. Pillar topics and applications

(1) Topic 1#: detection and evaluation of geometric quality

Topic 1# focuses on the detection of the geometric quality of PCEs and the evaluation of the detection results. As Table 1 and Fig. 4 demonstrate, advanced paradigms of 3D laser scanning, photogrammetry, and imaging have empowered quality inspection with digital technology-driven solutions. Meanwhile, these keywords, such as point cloud, reconstruction, and visualization, indicate the main implementations of DITs. Geometric quality is the key issue for the quality testing of PCEs [128] and has been extensively studied. Based on the previous analysis, the following can be concluded: in the fabrication phase, the factory quality of PCEs and the satisfaction of field installation requirements are ensured. In the transportation stage, the PCEs are tested for possible undesirable vibrations. In the construction stage, the internal damage, grout compactness, positioning accuracy, and other indicators are tested to analyze whether the construction deviation meets the acceptance requirements. In the operation and maintenance phase, the focus is on the structural performance of the PCEs. In this topic, existing DIT studies have basically implemented the geometric quality detection function of PCEs, although the scope is rather limited [61]. Notably, the current study of one type of DITs does not detect all types of quality problems of PCEs, which indicates that integrating multiple DIT techniques is a development direction that can improve detection efficiency [111].

(2) Topic 2#: detection and evaluation of non-geometric quality

Topic 2# discusses the detection of non-geometric quality of PCEs and the evaluation of the detection results. As shown in Table 6, acoustic emission appeared 30 times as a keyword with the highest attention, followed by ultrasound. Notably, the geometric quality detection and non-geometric quality detection of PCEs are not independent of each other. The geometric quality information and non-geometric quality information acquired by DITs are left and right to each other. For example, 3D laser scanning acquires point cloud data including laser reflectance (related to surface roughness and concrete maturity), temperature (related to concrete maturity), and color (related to cracks). Based on big data and derivative-free optimization [129], analyzing and simulating the dynamic processes of production, maintenance, transportability, and installability of PCEs are necessary to improve the quality inspection capability of PCEs by realizing the advantages of geometric quality inspection results and non-geometric quality inspection results.

(3) Topic 3#: schedule management in the context of multi-technology integration

Topic 3# focuses on how to integrate multiple technologies and methods and to advance management application. First, BIM is the keyword with the highest score in this topic, appearing 42 times with an average normal citation of 1.87, followed by RFID, as shown in Table 1. These studies have revealed the applications of multi-technology-based progress management. All these keywords can be concluded to indicate that DIT research objectives are not only for quality inspection only but also for progress management, which is a very important application direction. Based on BIM and 3D laser scanning, the spatial and temporal information of the construction site is assembled in the 4D model, which facilitates the reasonable and scientific setting of dimensional quality tolerance benchmarks for PCEs [63], the development of construction schedule [94], and the visualization of construction management [48].

(4) Topic 4#: data-driven MiC information management

Topic 4# information management and information theory are used as the theoretical bases for the processing of quality inspection data (see Fig. 9). They combine the information acquired by DITs to construct integrated data processing system for MiC, which has formed an important topic. The final MiC project is coordinated by a variety of PCE supply and construction according to the design and construction plan. The MiC supply chain has many stakeholders; the whole workflow is one way from upstream to downstream, whereas the flow of information is a two-way process [130]. Information of PCEs is created, stored, accessed, updated, and delivered multiple times at various stages. Therefore, information transfer is a very critical part of the MiC supply chain but also has complexity and uncertainty. Owing to the ability of BIM to acquire and integrate information at different phases and digital twin to access data in real time [131], the synergy between the two in supporting DITs has received much attention [87,132].

6. Current challenges and future directions

6.1. Fusion of DITs

Co-occurrence analysis of keywords and systematic evaluation of DITs have shown that single DITs dominate the research field with fewer studies of fusion DITs. With the increasing complexity of PCEs and the need for digitization, a broader range of requirements exist for quality-related information and influencing factors. However, each DIT has its own limitations, including detection metrics and processing efficiency (see section 5.2). Therefore, fusing multiple DITs and performing multi-source data information fusion are another feasible research directions when the application effect of individual DITs cannot meet the detection needs. Regardless of the development of individual DITs, merging the advantages of various DITs together to develop new DIT processing can be better adapted to the changes in detection targets [133]. For example, point cloud-based DITs, which combine true color image-based DITs and waveform-based DITs, expand the data standards of point clouds and perform multi-source data for information fusion. Given the reliability and validity of DIT fusion, future research needs to collect further empirical data to prove this idea.

6.2. Quality inspection for the whole process

From mold manufacturing to mold use, from rebar tying, grouting, mold removal to maintenance, the quality of each link in the production process of PCEs is intertwined. When a problem exists in one link, it will also affect the other links, which will inevitably affect the quality of the MiC project in the end. Therefore, based on the production process in section 3.3, using DITs in section 5.2, for the whole process of PCEs production, for different processes, operators, and decision managers, based on internet of things (IOT) and cloud [134], implementing a process-oriented, automated quality inspection system for multi-stakeholder units in construction projects is an important direction for future research. Although a number of research systems have explored the local automation of MiC quality inspection, a large number of quality issues urgently require the introduction of automation, full processes, and monitoring mechanisms that can provide real-time feedback and updates [135]. Moreover, the boundaries and standards for the storage, use, and management of data generated by the quality inspection process at different stages of the whole life cycle of MiC should be clarified. 5G, big data, and other technologies should be combined to establish a quality inspection database to further enhance information interaction and interoperability and help strengthen decision support [121].

6.3. *Real-time inspection*

Section 3.3 has revealed a limited spectrum of DITs for quality inspection in the lifecycle phases of MiC. Most of them focus on the identification of quality defects after the occurrence of quality problems (PCEs of finished products) and rarely carry out real-time detection when the quality problems are about to occur and are occurring [51]. Compared with traditional construction, MiC shifts a substantial amount of on-site work to prefabricated component factories. However, the current MiC industry persistently has a labor-intensive characteristic. Most workers lack sufficient experience to react to quality problems, resulting in avoidable but not successfully avoided losses. In addition, most of the current studies focus on quality inspection, such as dimensioning, after PCEs are completed, which can result in some waste of material and capacity if the quality is unsatisfactory [121]. Despite considerable efforts in identifying quality defects in the factory and on site, quality problems cannot be eliminated, especially with the increased complexity of prefabricated components. Future research that enables real-time monitoring and alerts could be effective in avoiding eventual losses.

This is what we believe is an important way to achieve intelligent production of MiC in the future: to design movable all-round 3D inspection equipment by integrating multiple groups of LiDAR, infrared thermal imager and cameras. The objects of study are common MiC compositions, which are linear (e.g. beams, columns), faceted (e.g. panels, partitions), curved (e.g. type and L-shaped facades) and three-dimensional (e.g. pre-assembled washrooms, modular fully pre-assembled bedrooms) in the 3D assembly phase. We classify various production equipment (e.g. molds), intermediate products (e.g. steel cages) and finished products as objects to be tested in different processes before, during and after fabrication, and define corresponding all-round 3D inspection solutions to achieve real-time, full-process inspection. At the same time, it can quickly and globally align multiple LiDAR measurement data, combine thermal imaging and true-color 2D high-definition image data, expand the LAS data standard for point clouds, fuse multi-source data, and publish the fused point cloud inspection results in various common point cloud formats such as LAS and PLY.

6.4. *Deep application of digital twin*

According to the analysis in section 4.2.3, the application of digital twin in the quality inspection domain is still in its initial stage. Promoting the deep application of digital twin involves two levels of twin modeling and twin interaction, twin modeling provides unified model representation and access, and twin interaction provides unified interaction semantics. Specifically, based on the designed CAD/BIM standard data and related technical specifications, the design rules of the object to be tested (such as local symmetry), combined with the simulation of the whole process of the operation of different objects to be tested, a twin model that can reflect the actual state of the object to be tested in real time is established. According to each process identified in section 3.3, the key processes are selected and the twin model is compared with the BIM model to automatically produce accurate quality inspection results. However, there are limitations in the current automated point cloud segmentation algorithms for multiple geometric dimension-related quality inspection (e.g., dimensions, cracks, deformation) and non-geometric quality inspection (e.g., concrete maturity), which is a key direction for future research in the field of point cloud processing.

7. Conclusion

DITs have not only transformed the way quality inspection is conducted but has also brought about a convergence of knowledge based on it. To analyze the current situation of DIT application in the MiC industry and propose the application knowledge related to DITs, this study analyzed the status of DIT application in the MiC industry and reviewed the state of DITs considering the concepts and key technologies. Through keyword co-occurrence analysis, current mainstream research topics were identified, including the detection and evaluation of geometric quality, detection and evaluation of non-geometric quality, schedule management in the context of multi-technology integration, and data-driven MiC information management. These data form the core of the application of DITs in the field of MiC quality inspection. This study uses each process as an entry point to analyze in detail the current state of application of DITs in the fabrication, transportation, construction, operation, and maintenance phases. In the systematic evaluation, five different categories of DITs are analyzed on the bases of a 3D structure consisting of time, knowledge, and logic dimensions. Then, future research directions are proposed, which are real-time inspection, fusion of DITs, quality inspection for the whole process, and deep application of digital twin.

The content of this study is more focused on the application of DITs in MiC quality testing, but the breadth of the topic may lead to ambiguity in the setting of inclusion criteria when searching the literature. Moreover, the literature in the target area cannot be fully collected. Nonetheless, this study still contributes to the academic community by summarizing the mainstream research topics based on literature review and discussion, proposing a bottom-up knowledge structure for the application of DITs and analyzing the shortcomings of existing studies and future research directions, which can promote new thinking about DITs in the academic community.

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CRediT authorship contribution statement

Clyde Zhengdao Li: Data curation, Methodology, Writing – original draft, Writing – review & editing, Funding acquisition, Project administration, Resources, Software. **Shuo Li:** Data curation, Formal analysis, Methodology, Resources, Writing – original draft. **Yingyi Ya:** Formal analysis, Investigation, Supervision, Writing – review & editing. **Vivian WY. Tam:** Data curation, Project administration, Writing – review & editing.

Declaration of competing interest

On behalf of my co-authors, we declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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