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Building information modeling (BIM)-based modular integrated construction risk management – Critical survey and future needs

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Abstract

Modular integrated construction (MiC) is an innovative construction technology wherein complete building modules are produced and preassembled in an offsite factory before their final installation on the building site. It is fundamentally different from and has many advantages over the traditional onsite construction technology. However, it still involves several risks. To successfully implement MiC projects, effective MiC risk management (MiCRM) is crucial. Building information modeling (BIM) and BIM-related digital technologies have been applied to facilitate MiCRM in recent years. While numerous MiC studies exist, a critical analysis of BIM-based MiCRM is still missing. This study aims to conduct a critical survey of BIM-based MiCRM, and to offer recommendations about research gaps and future research directions. This was achieved by systematically identifying and critically reviewing related publications from four outlooks: (1) MiCRM through BIM used alone, (2) MiCRM through BIM used alongside sensing and tracking technologies (STTs), (3) MiCRM through BIM used alongside 3D model creation and comparison technologies (3D-MCCTs), and (4) other applications. Results indicated that using BIM alone for MiCRM has focused more on the design phase. The overall idea to use BIM-STTs integration for MiCRM is very young. In this direction, BIM-RFID integration has received most of the attention, although BIM-GIS integration

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is rarely explored. There are limited works around integrating BIM with 3D-MCCTs such as photogrammetry and augmented and virtual realities for MiCRM. While schedule- and cost-related risks have gained much attention in current BIM-based MiCRM research, facilities management, sustainability, and safety risks are largely ignored. Based upon identified gaps, this study suggested future research directions, including, e.g.: (1) BIM-based MiCRM software development, (2) fully automated and practical BIM-based MiCRM systems development, and (3) BIM-automatic rule checking integration for MiCRM. This study contributes to a solid understanding of BIM-based MiCRM and delivers a useful reference for its future practice and improvement within the industry.

Keywords: Industry 4.0; Digital technologies; Building information modeling (BIM); Modular integrated construction (MiC); BIM-based MiC risk management.

1. Introduction

The traditional onsite construction, which encompasses bringing materials, trades, and workers to site to construct a project, has been the accepted construction method for years. Therefore, it accounts for a significant percentage of the Architecture, Engineering and Construction (AEC) industry. In recent years, however, the industry has experienced diverse construction methods alongside the process of industrialization, causing the rise of offsite construction as a substitute for the onsite method. Offsite construction is the process whereby building elements, components, or modules are manufactured and preassembled before their final installation on site [1]. Its applications can be grouped into component subassembly, nonvolumetric preassembly, volumetric preassembly, and modular integrated construction (MiC) [2].

MiC – the most complete form of offsite construction – is a form of construction in which free-standing volumetric modules (completed with fittings, fixtures, and finishes) are manufactured and assembled in an offsite factory and then transported to the building site for installation [3]. With

MiC, around 80-90% of the whole building can be constructed inside the factory. Kamali and Hewage [4] documented the lifecycle benefits of MiC. These benefits, which include construction time, waste, cost and onsite manpower reduction, and improved safety, quality, productivity and sustainability, are the core motivators for using MiC in the AEC industry.

Despite the benefits, MiC still involves several risks. Whereas some risks are common to all AEC projects, others are unique to specific project types. MiC requires unique business model, design, supply chain, etc., which significantly differ from those of traditional construction [5]. It also has to adopt a manufacturing instead of a construction process and philosophy if the benefits have to be maximized [6]. These lead to unique risks in MiC projects such as MiC modules damage and installation errors, which could result in costly and time-consuming modifications/rework, poor quality, and schedule delays. These risks can disrupt the successful implementation of MiC projects, calling for effective risk management throughout the project. While the risk management models/frameworks for traditional construction are not directly applicable to MiC [7], traditional MiC risk management (MiCRM) is a manual, time-consuming, error-prone, paper-based, labor-intensive, and costly task [8]. The assessment is basically dependent upon personal experience, and the decision-making is typically based on knowledge-based intuition, diminishing efficiency in real-life practice [9].

To overcome these problems, there has recently been a new research trend of utilizing building information modeling (BIM) and BIM-related technologies to facilitate MiCRM – this innovation is termed in this study as BIM-based MiCRM. This study aims to conduct a critical survey of BIM-based MiCRM, and to offer recommendations about research gaps and future research directions. The following Section 1.1 discusses the knowledge gap addressed by and the contribution of this study, followed by Section 1.2 that provides a brief summary of this paper.

1.1. Knowledge gap and contribution

There are many studies on MiC risks, which were reviewed by Wuni et al. [5]. Although Wuni et al.'s review focuses on identifying the critical risks, there are studies that develop and apply BIM and BIM-related digital technologies for managing specific risks [10–14]. Most existing reviews [15–19] partially summarize the application areas, benefits, risks, and challenges of applying these technologies in MiC. Zou et al. [20] indicated that though several reviews of traditional risk management techniques exit, there was no extensive review of BIM-based risk management research within the AEC industry. They attempted to address this gap; however, their work focuses upon BIM-based risk management associated with traditional construction and does not address the unique features of MiC. There is no comprehensive survey of the state-of-the-art in BIM-based MiCRM. This study aims at closing this gap. The main contribution of this study includes (1) comprehensive survey of the current state-of-the-art in BIM-based MiCRM, and (2) recommendations about research gaps and future research directions towards an ultimate goal of improving BIM-based MiCRM in both academia and industry.

1.2. Paper summary

This paper is organized as follows. Section 2 describes the research methodology. Section 3 presents research background, including risk management basics, general MiCRM process, and information and communication technology (ICT) for MiCRM. In Section 4, a comprehensive survey of BIM-based MiCRM is presented. The relationship between BIM and MiCRM is first discussed, followed by detailed reviews of MiCRM through BIM used (1) alone, (2) alongside sensing and tracking technologies (STTs), (3) alongside 3D model creation and comparison technologies (3D-MCCTs), and (4) alongside other technologies. Section 5 discusses findings and future research needs and Section 6 concludes this paper.

2. Methodology

To realize a critical survey and analysis of BIM-based MiCRM, a three-stage research approach (adopted from Zou et al. [20]) was employed in this research. Studies not published in English and the topic of 'risks of implementing BIM and BIM-related technologies' are beyond the scope of this research. A selected study must use BIM alone or BIM alongside other digital technologies to tackle MiC risks. Studies using digital technologies without BIM are not selected, as this study focuses on BIM-based MiCRM.

Fig. 1 demonstrates the overall research approach. In Stage 1, basics, process, and major challenges of traditional MiCRM were summarized through a comprehensive literature review. This stage also involved identifying keywords for data acquisition to establish a foundation for the next stage. To reach a comprehensive dataset of present research on BIM-based MiCRM, several relevant studies [4,5,18,20] were referred to in determining the keywords. Consequently, selected keywords included those in Table 1.

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The keywords covered three aspects. The first aspect represented BIM as an ICT for MiCRM. The second and third aspects represented MiC and risk management topics, respectively. In Stage 2, the keywords were searched in three widely-recognized databases, *Scopus*, *Web of Science*, and *Google Scholar*, to collect relevant publications on BIM-based MiCRM. The keywords search was conducted using various combinations of the three aspects of keywords with "AND" and "OR" Boolean operators. For example, a keywords search was conducted for "BIM" OR "building information model*" AND "modular integrated construction" OR "modular construction" AND "risk". To minimize the chance of omitting relevant publications, the publication year range was not limited. Moreover, following Kamali and Hewage [4]'s strategy, the "document type" was not limited, preventing publication bias. In Stage 3, identified publications were critically reviewed to survey the state-of-the-art in BIM-based MiCRM, including gaps and future needs.

3. Background

In this section, basics, process, and challenges of MiCRM, and the need to use ICT for MiCRM are discussed.

3.1. Risk management basics

Risks have both positive and negative sides. This study focuses on MiC risks' negative side to facilitate the avoidance or mitigation of negative risks (threats) while exploiting or magnifying positive risks (opportunities). In MiC project context, risk is "the likelihood of a detrimental event occurring to the project" [21]. MiCRM is a process involving risk management planning, identification, analysis, response planning, response implementation, and monitoring on a MiC project [22]. MiC projects are one-off undertakings with several unique features such as offsite manufacturing. Such complexities generate enormous risks, rendering MiC riskier than traditional construction. When risks cannot be eliminated, as-early-as-possible identification and evaluation of risks becomes necessary for managing risks effectively [23].

There are numerous techniques for identifying and analyzing risks, which can be classified into quantitative and qualitative categories [20]. The former comprises environmental risk assessment, risk indices, etc. The later includes SWOT analysis, spreadsheets, etc. These techniques have been applied to risk management in both traditional construction [23] and MiC [7]. Despite being useful, they are still traditional techniques profoundly dependent upon experience and knowledge [24]. They are also only able to provide limited information [25]. Therefore, many studies indicate that traditional risk management can play only a limited part in magnifying efficiency within the real-world [26], highlighting the necessity to use ICT for MiCRM.

3.2. General MiCRM process

Despite several studies on the unique MiC risks, there are limited frameworks to manage these risks effectively. Enshassi et al. [27] attempted to fill this gap, however their developed framework manages only tolerance risks in modular design. So, there is still lack of a generic systematic MiCRM framework. Zou et al. [20] based on literature review and interviews to develop a general risk management framework for AEC industry. Sousa et al. [28] based on the ISO 31000:2009 risk management standard for a similar exercise. Because most existing risk management frameworks focus on traditional construction, they have limited applicability in MiC. Based on existing construction risk management frameworks, international risk management standards [29], and detailed literature review, this study develops a novel generic systematic MiCRM framework (Fig. 2). A long-term goal is for this framework to enable more effective risk management throughout MiC project lifecycle.

< Please insert Fig. 2 around here>

MiC is fundamentally different from traditional construction. One obvious difference is in the stakeholders involved. MiC involves more stakeholders; manufacturers, for example, represent additional participants [18]. It also has more phases. Fig. 2 presents a MiCRM framework that encourages stakeholders to work collaboratively for managing risks systematically. The core philosophy, identified within the ‘Risk Mitigation Model’, is that risks should be identified and mitigated as early as possible, especially during the planning and design phases. If potential risks could be effectively identified and planned for in these phases with proper corresponding control measures, then they can be prevented from causing problems in later project phases. Hence, the idea is to "design out" most of the foreseeable risks during the planning and design phases. The residual risks should be effectively managed in the manufacturing and subsequent phases. All relevant stakeholders must be involved right from the project start, explaining why the large light blue arrow in the framework points stakeholders to the planning and design phases. For example, as each manufacturer has their own proprietary system for manufacturing MiC modules, involving the inputs of the manufacturer and assembly company (main contractor) into the design upfront would help mitigate risks, e.g., constructability risks of the MiC design, leading to greater construction productivity [30]. Having dedicated risk management experts/department can also help in overseeing the entire MiCRM process with right expertise.

Certain challenges, however, in above process include higher requirement for: (1) effective communication and collaboration environment, (2) efficient information transferring and sharing, (3) decentralized decision-making, (4) real-time knowledge and experience capturing and analysis, (5) processes integration, (6) better coordination, (7) constant connectivity and (8) management of multidisciplinary and interdisciplinary knowledge and experience. Knowledge/experience attained from previous projects can be applied for contributing to future projects. Efficient management of this big database of human knowledge and experience along with accurate and seamless extraction and analyses of datasets [20] are critical to MiCRM success. As per current MiC practice in Hong Kong and Singapore [8,31], for instance, normally, the designer passes the design drawings to the main contractor, who then forwards it to the MiC manufacturer, who is usually an offshore one. Based on the design drawings, the manufacturer develops the shop drawings, which must be sent back to the main contractor and designer for approval. Modules production cannot start until the shop drawings are approved. Once the modules are produced, the manufacturer engages a third-party cross-border logistics company to transport them to the main contractor for assembly. Once the project is done, handing over takes place. Throughout these processes, individuals/companies may leave the project once their tasks are done and critical risk data might be lost if they are not suitably documented and shared with other stakeholders [32]. This is where BIM and other digital technologies can solve challenges of current MiCRM.

3.3. ICT for MiCRM

The fourth industrial revolution (Industry 4.0) represents the era of digitization. ICT is at the center of Industry 4.0 and can significantly improve risk management effectiveness [33]. It is critical to risk evaluation, hazard monitoring, and early warning and alert systems [34]. Billante [35] argued that as global AEC projects become more challenging, so does the intrinsic risk. And that innovative construction methods (e.g., MiC), regulations, materials, and features drive a constantly changing landscape necessitating stakeholders and firms to embrace ICT for risk management if they want to achieve success. Adopting ICT can have substantial impact on project risk management, assisting the delivery of quality projects safely and on budget and time.

Hence, with the rapid advancements in ICT, ICTs such as BIM, RFID, and GIS, have been used for managing risks in AEC industry in general and in specific project types. Zou et al. [36] applied BIM to managing risks in bridge projects. Du et al. [37] proposed a GIS-GPS-BIM-based method to control risks in subway station construction projects. According to Ahmad et al. [25], these ICTs aid decision-making and help overcome shortcomings of traditional risk management techniques. They also provide novel management and design tools [38] and can considerably facilitate communication and collaboration between stakeholders and organizations [39]. All these are key to MiCRM success. Thus, over the last few years, the development and adoption of BIM and BIM-related technologies for construction risk management has been augmented and extended to MiC. This development is critically surveyed and discussed in the next section.

4. Survey of BIM-based MiCRM

This section discusses the relationship between BIM and MiCRM and presents a comprehensive survey on current state-of-the-art studies on BIM-based MiCRM.

4.1. Relationship between BIM and MiCRM

BIM is both a game-changing, disruptive technology and a process. In fact, both BIM and MiC are game-changing, disruptive technologies. Their integration therefore plays a weighty role in transforming the AEC industry. As a technology, BIM assists project participants to visualize what is to be constructed in a virtual environment to resolve any issues before the actual construction [40], an integral part of risk management. BIM is a game-changing, disruptive technology, as it markedly changes project processes via digital integration. From a process standpoint, Autodesk [41] defines BIM as a process that starts by creating an intelligent 3D model and enables simulation, document management, coordination, integration, communication, and collaboration between project stakeholders.

Though studies using BIM to manage MiC risks do not usually refer to risk management purposefully, the BIM application process itself can be viewed as a systematic approach to risk management [42]. For example, the clash detection function of BIM is an effective way for automatically identifying and solving ‘clashes’ in design before they can become bigger problems in the project. Moreover, BIM facilitates early risk identification/analysis by providing an information-rich environment for preconstruction tasks like 3D visualization, forming a reliable basis for devising risk mitigation measures in advance [26]. It provides a data generator, database or platform to allow risk analysis by itself and other tools [43,20]. BIM can therefore serve as a risk management tool for MiC projects.

For MiCRM, BIM is used alone or alongside other technologies (BIM-related technologies). As Li et al. [19] showed, these BIM-related technologies can be classified into two categories: (1) STTs (RFID, barcode, etc.), and (2) 3D-MCCTs (laser scanners, photogrammetry, etc.). In the next subsections, the state-of-the-art of R&D on MiCRM through BIM used alone is first surveyed, followed by surveys on MiCRM through BIM used alongside STTs, and alongside 3D-MCCTs. Applications that do not fall in any of these three categories are discussed in “other applications”.

4.2. MiCRM through BIM used alone

Various risks exist in each MiC project phase and managing them effectively is critical to project success. Within the planning and design phases, one of the main risks is design errors [44]. BIM can handle this risk through automation. Alwisy et al. [14] developed a BIM-based automated system to easily detect and rectify errors in MiC design, extending their earlier work [45]. Sharma et al. [46] presented a BIM-based design prototype to mitigate rigidity in MiC design. BIM’s 3D parametric models were used to build knowledge-based frameworks for accurate MiC project cost estimation [47-49]. In practice, firms apply BIM to manage MiC design risks, leading to error-free designs and improved documentation quality [50]. BIM can manage risks in other MiC planning and design phase activities, e.g., scheduling [51,52], product information exchange [53], and modular coordination-related modeling/documentation [54].

In the manufacturing phase, there is often pressure on the manufacturer/supplier to effectively manage schedule, quality, and quantity risks and improve productivity. To support this, Lee and Kim [55] developed BIM-based 4D simulation models for scheduling, quality, and quantity management of modules manufacturing process. From individual module manufacturing processes perspective, the models help in identifying optimal processes by visual reviews. From quality perspective, they afford visualizations for tackling risks such as manufacturing errors.

Within the logistics phase, Bataglin et al. [56] extended the application of BIM 4D modeling in MiC to the logistics operations planning and control process in Engineer-to-order context. They proposed guidelines concerning how to use BIM to evaluate the risk of changes in production plans considering the impacts on logistics.

In the onsite assembly phase, assembly planning and scheduling are two main concerns. BIM was employed in creating an automatic assembly sequence and schedule generation system [57] with three components, MS Access, Autodesk Revit, and MS Project, connected by a Revit API. Exporting the generated sequence and schedule results to MS Project facilitates resource leveling and communication among project stakeholders. The effectiveness of BIM in aiding MiC modules assembly sequence planning was further illustrated by Wang and Yuan [58], who developed a BIM-based assembly sequence planning methodology.

We identify that most previous applications of BIM as a stand-alone tool for MiCRM focused on the design phase where BIM is often used to generate and share design information. This may be because generating and sharing design information represents one key function BIM was customarily developed for [41]. During MiC design phase, BIM is applied for conceptual design, detailing, analysis and documentation. Data generated here could inform preconstruction activities like scheduling and cost estimation. Albeit this same data could further inform activities in later project phases, e.g., logistics, it is rare to apply BIM as a stand-alone tool for managing risks in such phases. This observation concurs with that of Niu et al. [59], who detected that using BIM in MiC logistics phase is largely ignored because of lack of geospatial data in BIM models. Due to shortcomings, using BIM in such phases typically demands combining it with other technologies (GIS, etc.), as illustrated in subsequent sections.

Besides, while most previous studies focused on applications in individual phases, only few studies explored integration of various phases for optimizing MiC supply chain. This could explain why lack of supply chain phases integration is the most critical problem in MiC [60]. This problem must be solved, to unlock MiC's full value. Babič et al. [61] developed a BIM-based system to integrate design, manufacturing, and construction processes of MiC projects. This work is useful to optimizing MiC supply chain, but logistics, operation and maintenance, deconstruction, and recycling/landfill phases (Fig. 2) were not integrated.

4.3. MiCRM through BIM used alongside STTs

After discussing applying BIM alone for MiCRM in Section 4.2, this subsection discusses using BIM alongside STTs – RFID and GIS – for MiCRM.

4.3.1. BIM+RFID

Automatic identification and data collection (AIDC) is a family of ICTs for identifying and tracking objects [62]. RFID is part of this family. It utilizes electromagnetic fields to automatically identify and track objects based on RFID tags attached to them. In MiC domain, these objects include people, modules, equipment, etc. See MHI [62] for more information about RFID.

The need to integrate BIM with RFID to improve MiC delivery efficiency is recognized. Li et al. [11] proposed an RFID-enabled BIM platform to improve the schedule performance of MiC. Smart construction objects (SCOs) enabled by IoT and cloud technology were developed along with an RFID-enabled gateway for managing the SCOs. A BIM platform was established for real-time decision-making. Zhai et al. [8] replicated Li et al. [11]'s effort with some improvements. One of which being using smart-trinity-tag consisting of RFID tags, QR codes, and NFC tags instead of using only RFID tags in their developed IoT-BIM platform. Such approach helps reduce the chance of losing information because of failure of one tag type. Using BIM to help onsite modules assembly has several benefits, e.g., providing a useful tool to manage physical and digital presentations [12]. However, with lack of real-time visibility and traceability, and inefficient data exchange, these benefits cannot be fully achieved. Li et al. [12] reported a platform based on IoT-BIM-RFID-cloud-VR integration to solve these issues. Similarly, Zhong et al. [63] explored an IoT-RFID-BIM platform for real-time visibility and traceability of modules manufacturing, transportation, and assembly. All above-mentioned studies focused on information visibility and traceability for monitoring project progress in real-time.

Cheng and Chang [64] devised an RFID-BIM platform to manage MiC lifecycle information, where RFID helps store and retrieve information, and BIM creates database for building materials and components. Altaf et al. [65] created an RFID-BIM-simulation-based system to automatically plan and schedule MiC manufacturing process. Their research showed that RFID data can contain “considerable noise”, such as corrupted times due to waiting times during project tasks. However, most previous applications did not treat this noise, which could affect the accuracy and efficiency of their developed BIM-RFID systems. Noisy RFID data may shift decisions from optimal results. A way to treat this noise is to apply algorithms, e.g., random sample consensus algorithm, to extract noise-free records for forming the basis for decisions [65]. There exist other studies applying BIM-RFID integration for MiCRM [13,66–70].

We observe that using BIM-RFID integration often necessitates using other ICTs, IoT, cloud computing, mobile devices, etc., too. One reason is that to be able to use BIM-RFID integration to track status of MiC objects, these objects must be converted into *smart objects* that can be tracked in real-time over the internet or in the cloud. Real-time internet- or cloud-based tracking allows for better collaboration between remote project stakeholders.

4.3.2. BIM+GIS

While BIM provides process and product data, GIS provides geospatial data. Hence, integrating BIM and GIS is an effective way to introduce geospatial context into MiC design and construction [71]. This leads to safer, smarter, and resilient modular buildings, and reduced risk due to improved efficiency and prevention of critical data losses in various project phases [72]. By GIS data introducing geospatial elements into BIM models, MiC projects can be better designed and built within the context of their real-world surroundings.

Recently, there have been studies to explore how BIM-GIS integration can improve MiC. For example, based on BIM-GIS integration, Niu et al. [59] proposed a platform for optimizing MiC logistics. The platform has four layers; project 3D, city 3D model, road network and logistics route layers; and could help mitigate MiC logistics risks such as delayed or too early delivery of modules to site. A case study was presented to demonstrate using the platform for identifying optimal logistics scenario of trailer routes to meet onsite installation time of MiC projects. Despite its value, the platform only optimizes trailer routes from modules storage yards to construction sites. It does not optimize routes from manufacturing yards to storage yards or construction sites.

We find that the overall idea to apply BIM-STTs integration for MiCRM is very young, as most studies are quite recent, with BIM-GIS integration receiving very limited attention. Further studies in this direction are promising. While most current studies focus on BIM-RFID integration, studies integrating BIM with STTs like labels, voice recognition, biometrics, smart cards, and cubing and weighing [62] for MiCRM are uncommon. Meanwhile, BIM-voice recognition integration, for instance, can allow eyes- and hands-free task execution and progress reporting. Hence, this gap is worth filling. This study’s finding is justified by the fact that there are numerous suitable STTs in the marketplace, but applications in the AEC industry of these are not common [73].

4.4. MiCRM through BIM used alongside 3D-MCCTs

This subsection discusses using BIM alongside 3D-MCCTs – laser scanning, photogrammetry, AR, and VR – for MiCRM.

4.4.1. BIM+3D laser scanning

Quality assurance/quality control (QA/QC) is required to safeguard the quality of a MiC project. However, manual quality inspection is subjective, unreliable, labor-intensive and time-consuming. Automated systems are needed to overcome these issues. By BIM-laser scanning integration, Kim et al. [74] presented a technique to automatically inspect and assess dimensional quality of MiC objects. An as-built BIM was built from laser-scanned point-cloud data, and a BIM-based storage and delivery approach was developed to help project participants update and share dimensional quality assurance data through manufacturing and assembly phases. Wang et al. [75] reported a BIM-laser scanning-based quality assessment technique to estimate dimensions of MiC objects with geometry irregularities. Wang et al. [76] introduced a technique to automatically build as-built BIMs of MiC objects from as-built dimensions captured through laser scanning. All aforesaid applications focused on dimensional quality assessment aiming to hone the automation, accuracy, and reliability of dimensions estimation. Other applications in this direction include [77–82].

Some studies, instead, focused on quality control and tolerance analysis. Kalasapudi and Tang [83] developed a framework integrating laser scanning with BIM for detecting and analyzing fit-up problems in curved MiC units. A tolerance network provided a quality control framework for adaptive redistribution of manufacturing and installation errors to resolve fit-up problems in MiC. The risks of misalignments and inefficient tolerance analysis remained the focus in this case [84].

Though useful, current applications have limitations. They primarily focus on two issues: geometric quality assessment (GQA) and geometric quality control (GQC). GQA has seen most existing studies, where dimensional quality assessment is the main focus. Recent reviews [85,86] showed that concerning GQA, laser-scanned point-clouds can be used for three purposes – dimensional, deformation/deflection, and surface quality assessments. Deformation/deflection and surface quality assessments remain to be sufficiently explored with BIM-laser scanning integration in MiC realm. The foci of research on dimensional quality assessment include the sizes, shapes, positions, etc. of MiC objects. More future studies on positioning are needed. Extant research using BIM-laser scanning integration for GQA/GQC in MiC further focus more on four-sided shaped and flat-surfaced objects (e.g., rectangular objects) for convenience. Though complex geometries, like cylindrical and interwoven ones, pose greater challenges to quality assurance in MiC [83], they are largely overlooked, representing a promising direction for future research. BIM-laser scanning integration holds promise for not only automated QA/QC, but also several other problems throughout a project – building renovation, safety management, heritage applications, etc. [85] – which have received limited attention in BIM-laser scanning-based studies in MiC field.

Previously developed BIM-laser scanning-based techniques for MiCRM also have limitations. Most of them need to refer to the as-designed BIM, in creating the as-built/as-is BIM [75]. Scan data offer as-built/as-is conditions, whereas BIM provides as-designed conditions. In reality, the latter might be missing and even when it is available, there may be significant variances between the as-designed and as-built/as-is conditions. The applicability of most of the techniques is limited, without an as-designed BIM. Most techniques were developed based upon only one surface scan from only one scanner location for dimensions estimation, which limits the scan data resolution/quality. Although the needed data quality could be specified based on the particular application's requirements [85], multiple scans from multiple scanner locations may improve data quality. Transferring as-built/as-is dimensions to BIM was also not automated in most of the techniques. Data preprocessing to eliminate noise can improve scan data quality. More BIM-laser scanning-based techniques addressing above issues [76] must be developed to improve MiCRM.

4.4.2. BIM+photogrammetry

Photogrammetry, like laser scanning, can acquire point-clouds and integrate with BIM for MiCRM. Photogrammetry is the method of acquiring information from photographs. It comprises processing photographs of physical objects (e.g., MiC modules) to generate 3D digital models/information of them. There are several studies [87] explaining both laser scanning and photogrammetry, but studies using BIM-photogrammetry integration for MiCRM are scarce. One of limited efforts is own to Faltýnová et al. [88]. Even in this study, instead of using just BIM-photogrammetry integration, BIM-photogrammetry-laser scanning integration was used to create a method for renovating modular façades of buildings. It was concluded that the method can lead to fast, cost-efficient building renovation with minimal disturbances to occupants.

The field needs further studies applying BIM-photogrammetry integration to MiCRM. In this future research direction, BIM-photogrammetry-laser scanning integration implementation is still recommended because photogrammetry has shortcomings. For example, it is easily affected by darkness. This can be overcome by laser scanning albeit it also has limitations photogrammetry can overcome. Therefore, photogrammetry and laser scanning are viewed as complementary technologies whose integration “can lead to more accurate and complete products” [89]. There are three types of laser scanners: terrestrial, airborne, and mobile laser scanners [86]. Whereas current applications of BIM-photogrammetry-laser scanning integration have typically used terrestrial laser scanners where scan data acquisition necessitates manual movement of the scanner to different locations, future research could employ airborne or vehicle-borne laser scanners for deeper automation of data acquisition. It could also employ aerial photogrammetry and/or closerange photogrammetry [90]. The former assisted by an aircraft or a drone is recommended in situations, such as upper-level exteriors of high-rise modular buildings, where it may be difficult or dangerous to use the latter assisted by humans.

4.4.3. BIM+AR

AR combines the real and virtual worlds, by augmenting the real world with virtual data/objects. It blends information produced by computer into an individual's view of a real-world environment, thereby providing a composite view, of both the real and virtual worlds. AR's biggest benefit is in providing virtual information to make real-world tasks easier for humans to perform. AR is typically applied in entertainment industries. Given its benefits, it is recommended to AEC industry. Wang et al. [91] proposed a framework for integrating BIM with AR so that the physical context of AEC tasks can be visualized in real-time. Chu et al. [92] investigated the effectiveness of integrating BIM with AR to augment AEC tasks efficiency. These studies suggest that BIM-AR integration can enhance tasks efficiency.

However, there is still limited research investigating using BIM-AR integration in MiC to identify potential problems, tackle risks, and improve tasks efficiency. A real-time 4D BIM-based AR system for MiC progress monitoring has only recently been invented by Lin et al. [93]. This system compares as-designed AR models with as-built sites and has a markerless AR registration method for linking 4D BIM data with as-built ones. It helps avoid modules assembly errors through offering a helpful tool for assembly schedule control and sequence monitoring. Tang et al. [94] developed a workflow for BIM-AR-based MiC design visualization and installation to allay risks such as "unreasonable design". BIM-AR application in MiC deserves more exploration. Such works would be more effective when BIM-AR integration is executed alongside STTs like RFID (Section 4.3.1) [91]. A reason is that although 3D-MCCTs help capture/analyze data from the real environment, they do not enable objects to be smart in regard to communicativeness, autonomy, and awareness for enhancing MiC efficiency [19].

4.4.4. BIM+VR

Both VR and AR are immersive technologies. They emulate the real world through the virtual world by surrounding users with a sensual feeling, thereby building a sense of immersion. The main difference between VR and AR is that VR completely replaces the real world with a virtual one, whereas in AR, the virtual world complements the real world rather than completely replacing it. To be precise, VR fully immerses users inside a virtual environment. Once immersed, users are unable to see the real world. AR, conversely, allows users to see the real world together with virtual objects meant to improve users' perception of reality. To put this in context, in MiC, VR can be used to, for example, establish a walk-through simulation of the inside of a new modular building, while AR can be used to show parts of the building superimposed upon a real-world view. As such, VR and AR can assist users to better understand MiC design solutions. However, they are limited by their inability to facilitate interoperability and collaboration among project participants. This shortcoming could be addressed by depending on openBIM and industry foundation classes (IFC) schema capabilities to allow for communication and simultaneous multiuser among applications via BIM server concept. Against this background, Rahimian et al. [95] developed an OpenBIM-Tango integrated virtual showroom for offsite manufacture of self-build housing that interactively presents BIM models and IFC data to users within VR and AR environments in real-time. Not only can the showroom streamline the design process via early involvement of stakeholders in decision-making. It can also solve interoperability issues of the MiC industry. Like BIM-AR integration, BIM-VR integration has seen limited applications in MiC, warranting future research attention.

4.5. Other applications

This subsection discusses using BIM alongside other technologies other than STTs and 3D-MCCTs for MiCRM.

4.5.1. BIM+simulation+optimization

Aiming at improving the performance and productivity of MiC manufacturing, Barkokebas et al. [96] used BIM-simulation integration to maximize the effectiveness of using data available within BIM models of MiC projects. BIM-particle swarm optimization-simulation integration can solve scheduling problems in MiC [43]. It can automatically generate optimized project schedules, reducing schedule risks, which otherwise can result from human errors. Wang et al. [97] proposed a BIM-improved genetic algorithm (IGA)-based integrated method to address assembly sequence planning and optimization problem in MiC. IGA identifies optimal assembly sequence while BIM validates the optimal results by simulation.

4.5.2. BIM+SWT

The success of a MiC project largely hinges on early involvement of the manufacturer in the different project phases, particularly the design phase. Nevertheless, manufacturers' involvement can be hampered by the lack of links between their product catalogues and the project's BIM model. To overcome this problem, Costa and Madrazo [98] used semantic web technologies (SWT) to link product catalogues of manufacturers with BIM models.

4.5.3. BIM+context-aware cloud computing

Abedi et al. [60] identified the major risks in MiC supply chain, including poor coordination, improper planning and scheduling, wrong modules deliveries, lack of integration, poor production timing, poor control and supervision, and poor communication between stakeholders. A context-aware cloud computing BIM prototype was created for MiC supply chain management to mitigate these risks. After surveying existing research, the following Section 5 discusses findings and future research needs.

5. Discussion and future needs

This study has surveyed the current state-of-the-art in BIM-based MiCRM, based upon which Table 2 offers a list of 47 potential risks in MiC projects together with BIM-based risk management strategies to tackle them. Previous reviews [5] documented MiC risks but did not provide (BIM-based) strategies to manage them and our documentation is also more comprehensive. The risks are classified into six categories: planning and design, manufacturing, logistics, onsite assembly, multi-phase, and universal risks. The first four categories are developed based on MiC project phases. Two criteria in classifying factors are "the context of the study itself and the body of underlying theory" [99]. Accordingly, the project phases from MiC project management theory are referenced in developing the risk categories. The multi-phase risks can occur in multiple, but not all, phases. For example, "inefficient verification of modules due to ambiguous labels" (MS1) can occur in manufacturing, logistics, onsite assembly, operation and maintenance, deconstruction, and recycling/landfill phases, but not in planning and design phase. The universal risks, e.g., "poor communication between stakeholders" (U1), can occur in all phases. Table 2 lacks operation and maintenance-, deconstruction-, and recycling/landfill-specific risks, because of dearth of BIM-based MiCRM studies on them. This gap should be filled. Due to word limitation, the four risk categories focusing on MiC project phases are discussed as follows.

< Please insert Table 2 around here>

Planning and design risks. These risks occur very early in the project and if unmanaged, can cause more risks in the project later. Design errors (PD1) should not be tolerated in MiC because, unlike in traditional construction, in MiC, it is highly difficult to make any design changes (PD2) later in the project, especially in the onsite assembly phase where the modules have already been manufactured and transported for installation. And during modules manufacturing, fixing PD1 can be costly and time-consuming, adversely impacting project cost and schedule. PD1 can also cause several other risks such as inefficient (e.g., delays in) design approval process (PD12), inaccurate quantities takeoff and cost estimation (PD8), and manufacturing errors (M2) (in the manufacturing phase). Automating MiC design with BIM is an effective strategy to eliminate PD1. BIM allows automatic, instead of manual, review of MiC designs to discover and repair any errors (overlapping geometries, etc.) before approving shop drawings for modules manufacturing. Moreover, using BIM, shop drawings can be created without the need for cross-coordination and detailed checking between numerous drawings [50], managing the risk of long design hours (PD5). Another benefit of BIM automation of MiC design is that as BIM is an object-based parametric design technology, throughout the design process, PD2 can easily be managed because once an object is modified, all other related objects are also automatically modified.

Manufacturing risks. Whereas most risks in the planning and design phase can be managed with BIM alone, in the manufacturing and subsequent phases, integrated technologies are required for managing most risks. Poor production planning and scheduling (M1), for instance, can jeopardize the success of a MiC project. Such risk can be handled via integrated systems such as BIM-RFID-simulation-based integrated system. In such system, RFID can be used to automatically acquire real-time production data, which can then be utilized for building a simulation model, which when integrated with an optimization algorithm, leads to automatic optimization of production plan and schedule [65]. One key role of BIM in this system is to feed information on building elements into the simulation model and RFID printer.

Logistics risks. Logistics is one of the most critical and challenging aspects of MiC. Not only must heavy/bulky modules be transported, but related regulatory requirements should also be met. Five main MiC logistics risks are identified, including delayed or too early delivery of modules to site (L1), human errors-caused logistics information inconsistency (L2), wrong modules deliveries (L3), misplacement in the warehouse due to carelessness (L4), and inefficient overall logistics management (L5). Once L5 is well managed, L1-L4 may automatically be managed. A BIM-based strategy to manage L5 is to integrate BIM with RFID for *intelligent* MiC logistics management. With a BIM-RFID-based intelligent MiC logistics management model, full lifecycle monitoring of MiC objects, and improved overall efficiency through real-time sensing, uploading, and tracking of information (e.g., materials and production information) can be achieved [66]. There can also be effective communication between the factory, transportation and onsite crews to ensure right and just-in-time (JIT) deliveries of modules to site.

Onsite assembly risks. MiC introduces to the AEC industry a new problem called assembly sequence planning (ASP), a popular problem in the manufacturing industry. A modular building with “n” number of modules has “n!” assembly sequences from which determining the optimal assembly sequence is very difficult. ASP aims to determine this optimal assembly sequence, which is necessary to reduce assembly time and cost and bolster quality. Inefficient assembly sequencing (OA1) is thus detrimental to the schedule, cost, and quality of MiC projects. To address this risk, BIM can be combined with optimization algorithms (e.g., IGA) in finding the optimal assembly sequence from the possible assembly sequences [97]. Addressing OA1 can contribute to addressing other onsite assembly risks like modules installation errors (OA5).

It is identified in Section 4 and Table 2 that for MiCRM, BIM can be used alone or alongside other digital technologies, namely STTs and 3D-MCCTs. This survey is conducted to understand the up-to-date developments and efforts, besides relevant research gaps and opportunities. It is found that most efforts on using BIM alone to manage MiC risks focus on the design phase. Many new MiCRM systems have been developed, integrating BIM with other digital technologies. These integrated systems are useful tools in managing MiC risks. Yet, most are not yet sufficiently developed. Only few BIM-GIS-, BIM-photogrammetry-, BIM-VR-, and BIM-AR-based systems have been developed for MiCRM. The survey further showed that BIM-RFID- and BIM-laser scanning-based systems have received relatively more attention. But even so, they do not address several essential issues in MiC. For example, the BIM-laser scanning systems focus more on dimensional quality assessment, while neglecting issues like safety management, building renovation, and heritage applications. We expect the use of BIM and BIM-related technologies for MiCRM to increase as its potential gets better understood and as Industry 4.0 evolves. As every technology has weaknesses, this study suggests future applications to use hybrid approaches to cover weaknesses. BIM may be combined with as many as possible STTs, 3D-MCCTs, etc. in any single application for robustness.

While Table 2 was developed based on MiC risks and BIM-based strategies used to tackle them in the reviewed studies, Fig. 3 summarizes this study's findings based on the foci and gaps of the reviewed studies as discussed in Section 4. Based on gaps of existing research, recommendations about future research directions to improve BIM-based MiCRM – including BIM-based MiCRM software, fully automated and practical BIM-based MiCRM systems, a holistic BIM-based MiCRM approach, an industry 4.0-DfMA-multidisciplinary-interdisciplinary system-thinking, BIM-automatic rule checking integration for MiCRM, and BIM-cybersecurity-blockchain integration for MiCRM – are also summarized in Fig. 3. These recommendations are discussed in the following subsections.

< Please insert Fig. 3 around here>

5.1. BIM-based MiCRM software

The first recommendation is about the development of BIM-based MiCRM software. Various BIM-based systems have been developed for MiCRM, each having its own focus. The implication in practice is that to achieve a complete BIM-based MiCRM, practitioners must use different systems for managing different risks at different project phases. This can cause acute information fragmentation problems, reducing efficiency and productivity. To solve this problem, future research could develop BIM-based MiCRM software to help conduct all MiCRM activities in one place. The software could be cloud-based to enable real-time usage among the typically dispersed MiC project stakeholders. Zou [42] proposed to develop BIM-based risk management software for bridge projects. Though such development could be extended to MiC, it has yet to be conducted. Another approach is to extend BIM dimensions to cover MiCRM. Since its emergence, BIM has been improved from 3D to 8D, as exemplified in Fig. 4 [100]. Drawbotics [100] indicated that "this technology has no limit since it is possible to add as many data as you want." Therefore, exploring the possibility to introduce a BIM dimension specifically designed for MiCRM might be interesting. A MiCRM plugin may also be developed for integration into any BIM software. The availability of a centralized BIM-based MiCRM software could help improve information management and thereby success in a MiC project as it provides a single source of information to prevent potential information fragmentation, inconsistencies or even loss in MiCRM.

< Please insert Fig. 4 around here>

5.2. Fully automated and practical BIM-based MiCRM systems

The second recommendation is two-fold. The first fold deals with developing fully automated BIM-based MiCRM systems. Previous studies claimed that manual handling is time-consuming and error-prone and therefore can significantly reduce efficiency in practice, a major justification for their development of BIM-based automated systems for MiCRM. It is thus interesting to observe that most of the developed systems still necessitate substantial manual handling in their implementation. In Liu et al. [43]'s study, "part of the simulation network still needs to be established manually." To enhance the performance of existing systems, future research should develop fully automated systems. Where full automation cannot be achieved, the possibility of developing systems that can detect and/or rectify human errors as they occur could be explored. Without these, manual handling and human errors may continue to limit efforts to improve industry practice through automation.

The second fold concerns developing practical BIM-based MiCRM systems. BIM-based MiCRM studies can be categorized into two levels: practical and proof-of-concept levels. Efforts at the practical level focus on developing systems that can be applied in the industry. Systems developed at the proof-of-concept level are far from industrial applications, as they only symbolize outcomes of restricted experimental works conducted to prove certain concepts. Only few of the now-developed BIM-based MiCRM systems are at the practical level. Most are at the proof-of-concept level and lack testing and execution in real-life project environments. Addressing this gap could help maximize the benefit of BIM-based MiCRM R&D to the industry and society.

5.3. A holistic BIM-based MiCRM approach

The third recommendation is about adopting a holistic approach to BIM-based MiCRM. As Fig. 4 shows, BIM has six dimensions ranging from 3D to 8D. Existing BIM-based MiCRM research pays much attention to the first three Ds (visualization, scheduling, and cost estimation), while paying limited attention to facilities management, sustainability, and safety risks. Visualization, scheduling, and cost estimation are all performed in project planning and design phase, and the substantial focus on this phase, as identified in Section 4.2, explains why schedule- and cost-associated risks have received much attention. There remain limited studies applying BIM to manage risks in facilities management phase of MiC projects. This may be attributed to the perception that the areas wherein MiC has caused *significant* disruption are design, manufacturing, logistics, and onsite construction, hence attention might have been biased toward other areas. Further studies are also needed to utilize BIM to enhance MiC projects sustainability and safety. One suggestion is to analyze how BIM can be used to monitor workers safety during installation of the heavy/bulky modules. It is commonly understood that MiC is surely a sustainable approach, as it reduces the impact of construction on the environment by waste, noise, and dust reduction. This understanding may be a contributing factor in the partial focus on sustainability risks. It should not be overlooked that sustainability is not just about waste, noise, and dust reduction. It covers other broader issues, e.g., CO_2 emissions. A holistic BIM-based MiCRM approach is needed to tackle the complete world of risks, to significantly improve the chance of MiC project success.

5.4. An industry 4.0-DfMA-multidisciplinary-interdisciplinary system-thinking

The fourth recommendation concerns embedding the concept of *industry 4.0-DfMA-multidisciplinary-interdisciplinary system-thinking* in the research and practice of BIM-based MiCRM. Zou et al. [20] suggested to implant a multidisciplinary system-thinking into the research and practice of BIM-based risk management in traditional construction. However, the system-thinking required for BIM-based MiCRM is much more than just a multidisciplinary one. Here, *an industry 4.0-DfMA-multidisciplinary-interdisciplinary system-thinking* is required. Industry 4.0 is upon the AEC industry, demanding it to transform through digitization, robotization, automatization, and additive manufacturing. BIM and BIM-related technologies help the industry to digitize and integrate vertical and horizontal value chains [101]. As for MiC, it moves construction tasks to manufacturing environment wherein high-level automation and robotics can be applied. By so doing, it naturally brings together experts with multidisciplinary and interdisciplinary background to complete the project. Also, MiC is a DfMA (design for manufacture and assembly) technology, meaning DfMA principles [102] must be followed to mitigate risks. From above discussion, it is clear that the concept of *industry 4.0-DfMA-multidisciplinary-interdisciplinary system-thinking* must be embedded in the research and practice of BIM-based MiCRM. Addressing this recommendation is important to ensure that necessary knowledge, skills and expertise are employed for effective BIM-based MiCRM, which is critical to the success of MiC projects.

5.5. BIM-automatic rule checking integration for MiCRM

The fifth recommendation deals with integrating BIM and automatic rule checking (ARC) for MiCRM. ARC means using computer software for assessing a design against rules, with outcomes such as “pass”, “fail”, “warning”, or “unknown” [103]. The MiC industry is regulated mainly at the state and local levels by agency and code administrators [104] and a MiC project must satisfy all local building codes. The MiC manufacturer may be an offshore one who may not be fully familiar with the local codes where the building is to be located, but still has to prevent any non-compliance. In MiC, all the same building codes and requirements for traditional construction must be met in addition to additional ones. In Hong Kong, for instance, “special traffic arrangement needs to be made for transportation of modules with width larger than 2.5 meters” [3]. Employing BIM-ARC integration to ensure all building codes and special requirements are met is critical to mitigate risks in MiC projects. Yet, such research efforts are currently missing.

5.6. BIM-cybersecurity-blockchain integration for MiCRM

The last but not the least recommendation is to integrate BIM with cybersecurity and blockchain technologies for MiCRM. As BIM and BIM-related digital technologies are used to enable project stakeholders to have a common data environment (CDE) to store, update, share and collaborate with the information they need throughout project lifecycle, the security of this information becomes increasingly vital. It is essential to protect the computer systems and networks enabling the CDE against cyberattacks and ensure project information are accessible to only those who are authorized. This problem is not a focus within current BIM-based MiCRM research and can be addressed with BIM-cybersecurity-blockchain integration in future work.

6. Conclusions

Different from previous studies that only reviewed MiC risks, this study critically surveyed the current state-of-the-art in BIM-based MiCRM for the first time. This study has both theoretical and practical contributions. For theory, the results provide the first inclusive agenda for leveraging and advancing BIM and its related technologies in MiCRM research with showcasing the existing research, highlighting fundamental problems to be addressed, and providing recommendations that give directions regarding how to address the shortcomings in defining future research. For practice, this study offers practitioners a synthesized and readily-available point of reference that captures the state-of-the-art of BIM-based MiCRM research, through which cutting-edge technologies and methods are introduced. This gives practitioners a benchmarking tool to assess their maturity in terms of applying BIM and its related technologies for MiCRM and also enhance their readiness for implementing BIM-based MiCRM. Moreover, this study developed a new MiCRM framework and a comprehensive documentation of potential MiC project risks together with corresponding BIM-based risk management strategies, which can be useful for MiCRM planning and application. The documentation helps practitioners appreciate risks they are likely to face in MiC projects and

BIM-based strategies to manage them, while the framework facilitates effective MiCRM through stakeholder collaboration.

Despite its contributions, this study has limitations. The technologies discussed along with BIM include RFID and GIS (STTs), laser scanning, photogrammetry, AR and VR (3D-MCCTs), and simulation, optimization, SWT and context-aware cloud computing (others). We appreciate that some STTs, for instance, were not discussed because of current dearth of research integrating them with BIM for MiCRM. Once the field matures, this survey may be improved by considering other technologies. Future work could also provide demonstrations on how to use the technologies. The next phase of this study focuses on developing a roadmap for integrating BIM and BIM-related technologies into MiCRM, while cost-benefit analysis of BIM-based MiCRM remains untouched.

We expect BIM-based MiCRM to expand in response to Industry 4.0. For successful implementation, the industry and academia are recommended to focus on people and develop their digital skills and culture through relevant education and training first. This is because the success of BIM-based MiCRM depends on not only the technologies used, but also the knowledge, skills, capabilities, creativity and culture of the people using them. Without proper education and training, it may be difficult to convince workers especially at the project site level to use digital technologies for identifying and communicating risks. The situation is even worse when they do not know how to use the developed technologies. It is also proposed to train and develop DfMA-oriented industry professionals and workers.

Declaration of interests

None.

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Table 1

Literature search keywords

Aspect	Keywords
BIM	“BIM”, “building information model”, “building information modeling”, “building information modelling”
MiC	“Modular”, “modular construction”, “modular integrated construction”, “modular building”, “modularization”, “modern methods of construction”, “off-site construction”, “offsite construction”, “off-site manufacturing”, “offsite manufacturing”, “off-site manufacture”, “offsite manufacture”, “prefabricated building”, “prefabricated construction”, “pre-cast construction, “precast construction”, “industrialized construction”, “industrialized building”, “prefabricated prefinished volumetric construction”
Risk management	“Risk”, “risk management”, “risk analysis”, “risk assessment”, “cost”, “time”, “schedule”, “safety”, “budget”, “quality”

Table 2

Potential MiC project risks and their corresponding BIM-based risk management strategies identified from literature.

Risk categories	Code	Risk factors	BIM-based risk management strategies	Key references
Planning and design risks	PD1	Design errors	BIM automation of MiC design	[14,50]
	PD2	Design changes	BIM automation of MiC design BIM-RFID integration for efficient communication among stakeholders BIM-RFID integration for efficient information transmission between design and manufacturing phases	[11,14]
	PD3	Design assumptions	BIM automation of MiC design	[14]
	PD4	Redundant design activities	BIM automation of MiC design	[14]
	PD5	Long design hours	BIM automation of MiC design Modular coordination rules-BIM process integration	[14,54]
	PD6	Insufficient integration of manufacturers into design phase	Using SWT to link product catalogues of manufacturers with BIM models BIM-AR-VR integration for early involvement of manufacturers in design phase	[95,98]
	PD7	Poor project planning and scheduling	BIM-PSOT-simulation integration for automatic generation of project schedules BIM-CCT integration for MiC supply chain management	[43,60]
	PD8	Inaccurate quantities takeoff and cost estimation	BIM automation of quantities takeoff and cost estimation	[47–49]
	PD9	Rigidity in design process	BIM automation of MiC design	[46]
	PD10	Design information gap between designer and manufacturer	BIM-RFID integration for passing design information to manufacturer without gaps	[11]
	PD11	Inefficient design data transition	BIM-RFID integration for passing design information to manufacturer without ambiguities	[11]
	PD12	Inefficient design approval process	BIM-RFID integration for efficient communication among stakeholders BIM-RFID integration for efficient information transmission between design and manufacturing phases	[11]
	PD13	Inconsistencies in modular design process	Modular coordination rules-BIM process integration	[54]
Manufacturing risks	M1	Poor production planning and scheduling	BIM-RFID-simulation integration for automatic modules production planning and scheduling BIM-simulation integration for design for MiC manufacturing BIM-CCT integration for MiC supply chain management	[60,65,96]
	M2	Manufacturing errors	BIM-based 4D simulation for managing module manufacturing processes	[55]
	M3	Inaccurate quantities takeoff for labor and material estimation	BIM-simulation integration for design for MiC manufacturing	[96]
	M4	Uninformative shop drawings	BIM-simulation integration for design for MiC manufacturing	[96]

	M5	Poor inventory control	BIM-RFID-barcode-QR code-IoT integration to achieve JIT inventory control BIM-simulation integration for design for MiC manufacturing	[67,70,96]
	M6	Inefficient material and labor resource allocation	BIM-simulation integration for design for MiC manufacturing	[96]
	M7	Lack of plans for using factory space and equipment	BIM-based 4D simulation for managing module manufacturing processes	[55]
	M8	Lack of understanding of process plans	BIM-based 4D simulation for managing module manufacturing processes	[55]
	M9	Changes in production plans	4D BIM visualization of site-assembly progress	[56]
	M10	Materials wastage	BIM-based 4D simulation for managing module manufacturing processes	[55]
	M11	Complications owing to performing manufacturing and material preparation tasks concurrently	BIM-based 4D simulation for managing module manufacturing processes	[55]
	M12	Poor manufacturing quality due to inability to inspect documents	BIM-based 4D simulation for managing module manufacturing processes	[55]
	M13	Inability to plan material purchases and storage because of lack of material quantity information for a particular process	BIM-based 4D simulation for managing module manufacturing processes	[55]
	M14	Ineffective production line balancing	BIM-RFID integration for effective modules production line balancing	[68]
Logistics risks	L1	Delayed or too early delivery of modules to site	BIM-GIS integration to achieve JIT delivery of modules to site BIM-RFID integration to achieve JIT delivery of modules to site	[11,59,69]
	L2	Human errors-caused logistics information inconsistency	BIM-RFID integration to facilitate information sharing between different ERP systems	[11,13]
	L3	Wrong modules deliveries	BIM-CCT integration for MiC supply chain management	[60]
	L4	Misplacement in the warehouse due to carelessness	BIM-RFID integration for real-time visibility and traceability	[11]
	L5	Inefficient overall logistics management	BIM-RFID integration for intelligent MiC logistics management	[66]
Onsite assembly risks	OA1	Inefficient assembly sequencing	BIM automation of assembly sequencing process BIM-improved genetic algorithm integration for assembly sequence planning and optimization	[57,58,97]
	OA2	Inefficient assembly scheduling	BIM automation of assembly scheduling process	[57]
	OA3	Interpreting shop drawings onsite	BIM automation of MiC design	[14]
	OA4	Breakdown of tower crane	BIM-RFID integration to improve interoperability between various stakeholders and their varied enterprise information systems	[11]
	OA5	Modules installation errors	BIM-RFID integration for efficient modules installation management	[11,93,94]

			BIM-AR integration for modules assembly schedule control and sequence monitoring	
Multi-phase risks	MS1	Inefficient verification of modules due to ambiguous labels	BIM-RFID integration for efficient identification and verification of modules	[11]
	MS2	Inaccurate as-built/as-is dimensions estimation	BIM-laser scanning integration for accurate dimensions estimation	[76–82]
Universal risks	U1	Poor communication between stakeholders	BIM-RFID integration for efficient communication among stakeholders	[11,55,60,94,95]
			BIM-CCT integration for MiC supply chain management	
			BIM-based 4D simulation for managing module manufacturing processes	
			BIM-AR-VR integration to facilitate communication between stakeholders	
	U2	Poor integration among stakeholders	BIM automation of MiC design	[14]
	U3	Poor coordination	BIM-CCT integration for MiC supply chain management	[60]
	U4	Lack of integration of supply chain phases	BIM-CCT integration for MiC supply chain management	[60,61,69]
			BIM-RFID-barcode integration for MiC supply chain integration	
	U5	Poor control and supervision	BIM-CCT integration for MiC supply chain management	[60]
	U6	Inefficient quality inspection procedures	BIM-RFID integration to embed design information in modules for further use	[11]
	U7	Low information interoperability among different ERP systems	BIM-RFID integration to facilitate information sharing between different ERP systems	[11,53]
	U8	Ineffective project information management	BIM-RFID integration for effective project information management	[64]

Note: MiC = modular integrated construction; BIM = building information modeling; SWT = semantic web technologies; CCT = cloud computing technology; GIS = geographic information system; JIT = just-in-time; PSOT = particle swarm optimization technology; RFID = radio-frequency identification; ERP = enterprise resource planning; IoT = the internet of things; AR = augmented reality; VR = virtual reality.

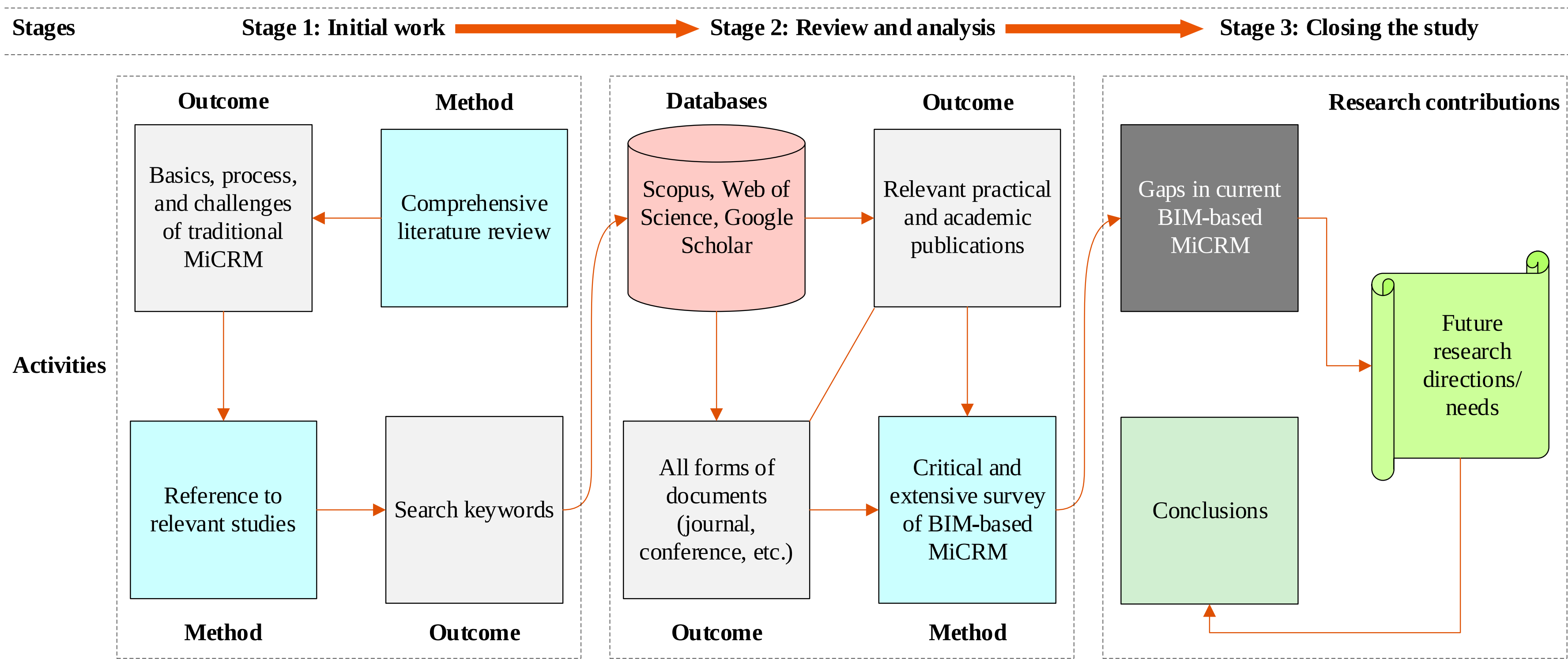

Fig. 1. Overview of research approach.

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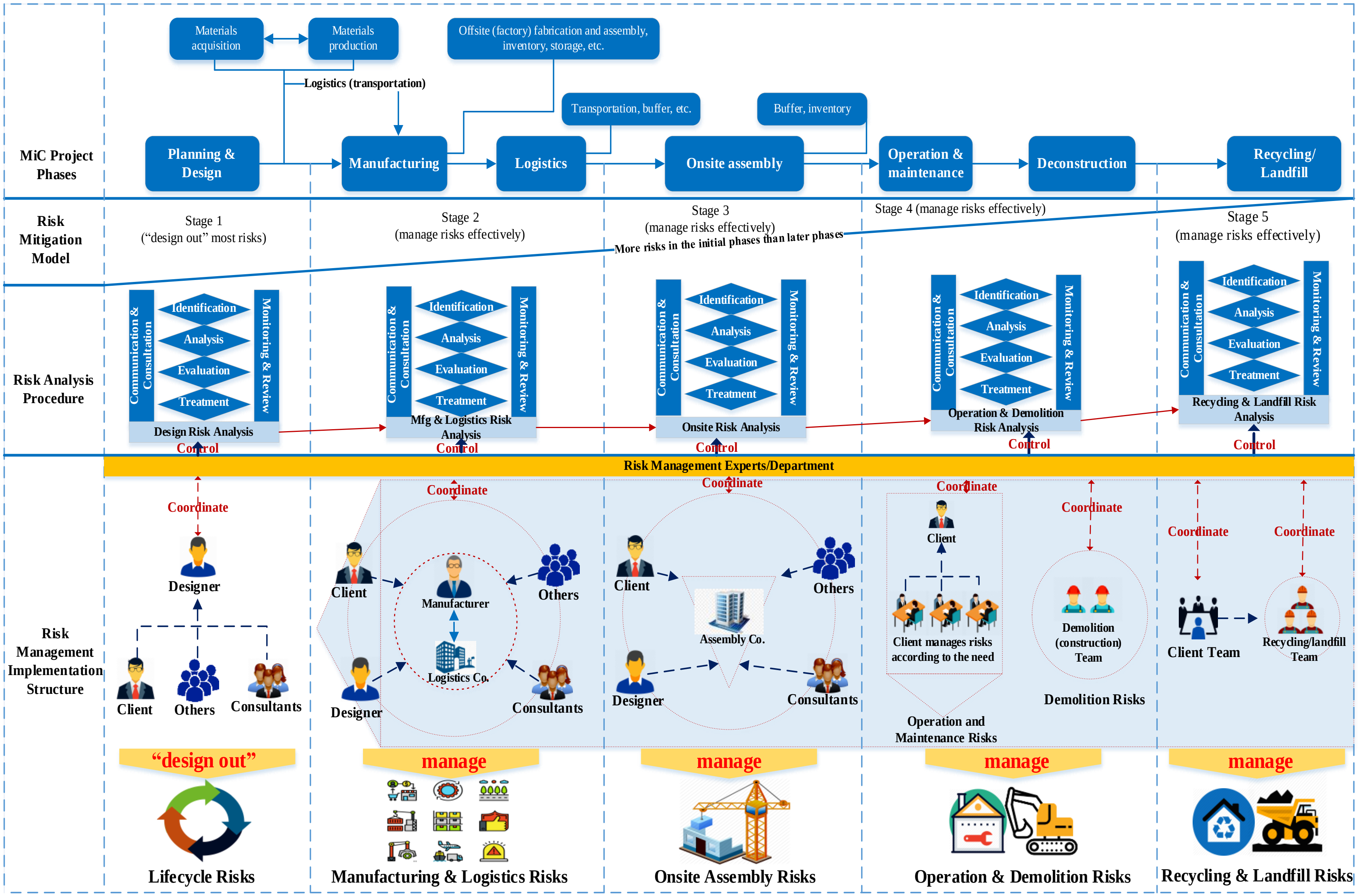

Fig. 2. Generic MiCRM framework. Adapted from Zou et al. [20] with MiC features integrated.

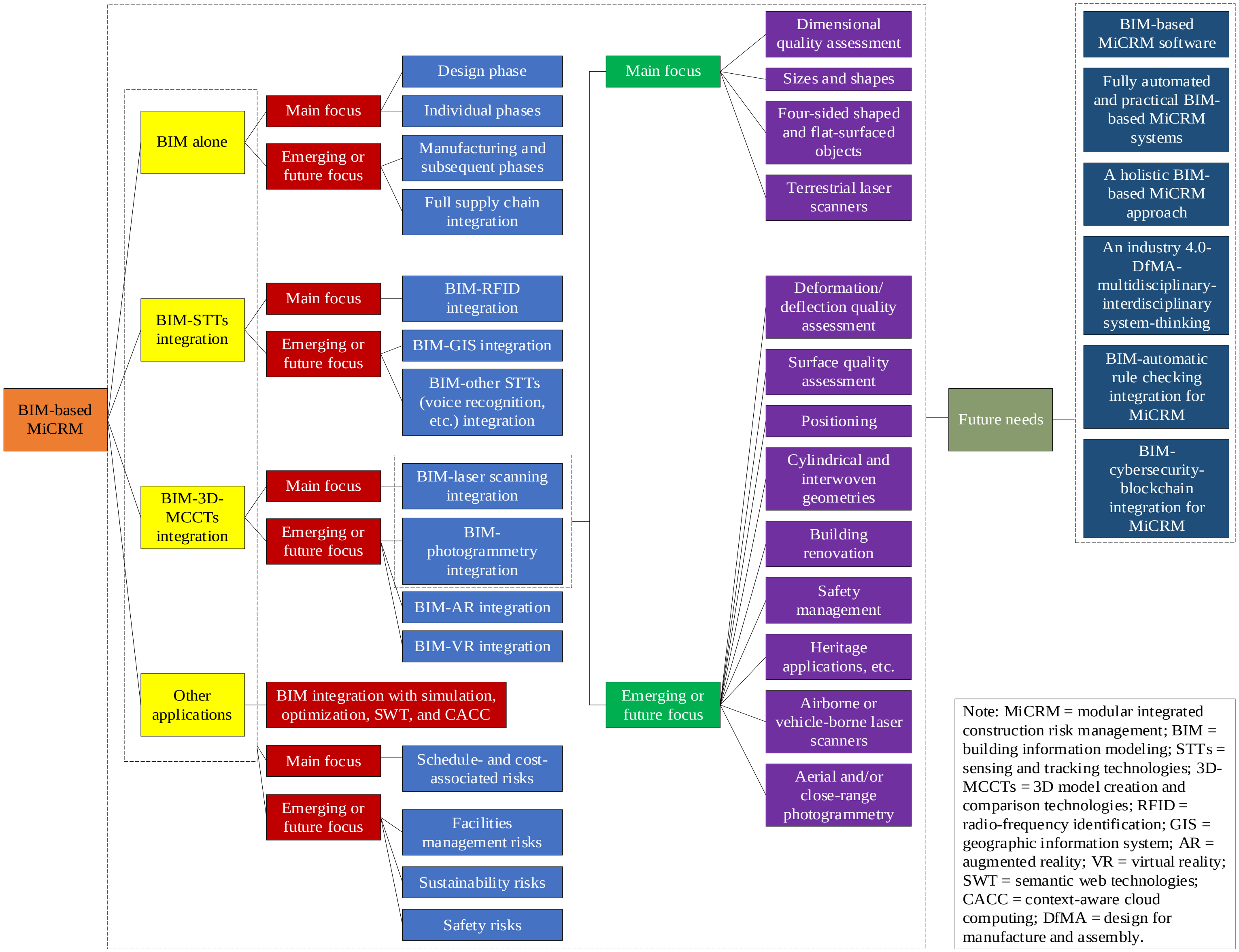

Fig. 3. Summary of findings.

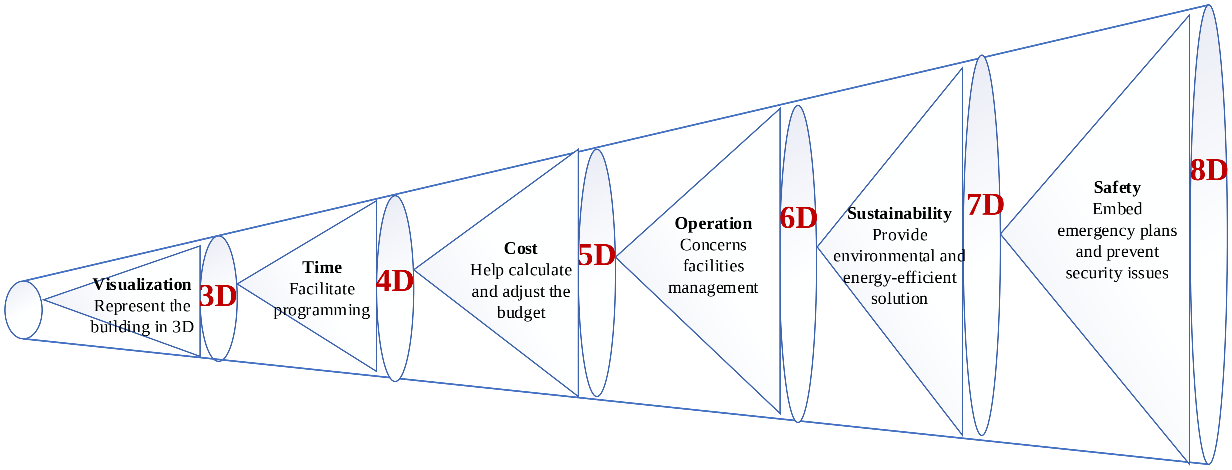

Fig. 4. BIM dimensions.