

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

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6 **Abstract**

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

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22 is rarely explored. There are limited works around integrating BIM with 3D-MCCTs such as
23 photogrammetry and augmented and virtual realities for MiCRM. While schedule- and cost-related
24 risks have gained much attention in current BIM-based MiCRM research, facilities management,
25 sustainability, and safety risks are largely ignored. Based upon identified gaps, this study suggested
26 future research directions, including, e.g.: (1) BIM-based MiCRM software development, (2) fully
27 automated and practical BIM-based MiCRM systems development, and (3) BIM-automatic rule
28 checking integration for MiCRM. This study contributes to a solid understanding of BIM-based
29 MiCRM and delivers a useful reference for its future practice and improvement within the industry.
30 **Keywords:** Industry 4.0; Digital technologies; Building information modeling (BIM); Modular
31 integrated construction (MiC); BIM-based MiC risk management.

32 **1. Introduction**

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

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

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

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

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

68 *1.1. Knowledge gap and contribution*

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

82 *1.2. Paper summary*

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

91 **2. Methodology**

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

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

104 < **Please insert Fig. 1 around here**>

105 < **Please insert Table 1 around here**>

106 The keywords covered three aspects. The first aspect represented BIM as an ICT for MiCRM.
107 The second and third aspects represented MiC and risk management topics, respectively. In Stage
108 2, the keywords were searched in three widely-recognized databases, *Scopus*, *Web of Science*, and
109 *Google Scholar*, to collect relevant publications on BIM-based MiCRM. The keywords search was
110 conducted using various combinations of the three aspects of keywords with “AND” and “OR”
111 Boolean operators. For example, a keywords search was conducted for “BIM” OR “building
112 information model*” AND “modular integrated construction” OR “modular construction” AND
113 “risk”. To minimize the chance of omitting relevant publications, the publication year range was

114 not limited. Moreover, following Kamali and Hewage [4]’s strategy, the “document type” was not
115 limited, preventing publication bias. In Stage 3, identified publications were critically reviewed to
116 survey the state-of-the-art in BIM-based MiCRM, including gaps and future needs.

117 **3. Background**

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

120 *3.1. Risk management basics*

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

130 There are numerous techniques for identifying and analyzing risks, which can be classified into
131 quantitative and qualitative categories [20]. The former comprises environmental risk assessment,
132 risk indices, etc. The later includes SWOT analysis, spreadsheets, etc. These techniques have been
133 applied to risk management in both traditional construction [23] and MiC [7]. Despite being useful,
134 they are still traditional techniques profoundly dependent upon experience and knowledge [24].
135 They are also only able to provide limited information [25]. Therefore, many studies indicate that

136 traditional risk management can play only a limited part in magnifying efficiency within the real-
137 world [26], highlighting the necessity to use ICT for MiCRM.

138 *3.2. General MiCRM process*

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

150 **< Please insert Fig. 2 around here >**

151 MiC is fundamentally different from traditional construction. One obvious difference is in the
152 stakeholders involved. MiC involves more stakeholders; manufacturers, for example, represent
153 additional participants [18]. It also has more phases. Fig. 2 presents a MiCRM framework that
154 encourages stakeholders to work collaboratively for managing risks systematically. The core
155 philosophy, identified within the ‘Risk Mitigation Model’, is that risks should be identified and
156 mitigated as early as possible, especially during the planning and design phases. If potential risks
157 could be effectively identified and planned for in these phases with proper corresponding control
158 measures, then they can be prevented from causing problems in later project phases. Hence, the

159 idea is to “design out” most of the foreseeable risks during the planning and design phases. The
160 residual risks should be effectively managed in the manufacturing and subsequent phases. All
161 relevant stakeholders must be involved right from the project start, explaining why the large light
162 blue arrow in the framework points stakeholders to the planning and design phases. For example,
163 as each manufacturer has their own proprietary system for manufacturing MiC modules, involving
164 the inputs of the manufacturer and assembly company (main contractor) into the design upfront
165 would help mitigate risks, e.g., constructability risks of the MiC design, leading to greater
166 construction productivity [30]. Having dedicated risk management experts/department can also
167 help in overseeing the entire MiCRM process with right expertise.

168 Certain challenges, however, in above process include higher requirement for: (1) effective
169 communication and collaboration environment, (2) efficient information transferring and sharing,
170 (3) decentralized decision-making, (4) real-time knowledge and experience capturing and analysis,
171 (5) processes integration, (6) better coordination, (7) constant connectivity and (8) management of
172 multidisciplinary and interdisciplinary knowledge and experience. Knowledge/experience attained
173 from previous projects can be applied for contributing to future projects. Efficient management of
174 this big database of human knowledge and experience along with accurate and seamless extraction
175 and analyses of datasets [20] are critical to MiCRM success. As per current MiC practice in Hong
176 Kong and Singapore [8,31], for instance, normally, the designer passes the design drawings to the
177 main contractor, who then forwards it to the MiC manufacturer, who is usually an offshore one.
178 Based on the design drawings, the manufacturer develops the shop drawings, which must be sent
179 back to the main contractor and designer for approval. Modules production cannot start until the
180 shop drawings are approved. Once the modules are produced, the manufacturer engages a third-
181 party cross-border logistics company to transport them to the main contractor for assembly. Once

182 the project is done, handing over takes place. Throughout these processes, individuals/companies
183 may leave the project once their tasks are done and critical risk data might be lost if they are not
184 suitably documented and shared with other stakeholders [32]. This is where BIM and other digital
185 technologies can solve challenges of current MiCRM.

186 *3.3. ICT for MiCRM*

187 The fourth industrial revolution (Industry 4.0) represents the era of digitization. ICT is at the
188 center of Industry 4.0 and can significantly improve risk management effectiveness [33]. It is
189 critical to risk evaluation, hazard monitoring, and early warning and alert systems [34]. Billante
190 [35] argued that as global AEC projects become more challenging, so does the intrinsic risk. And
191 that innovative construction methods (e.g., MiC), regulations, materials, and features drive a
192 constantly changing landscape necessitating stakeholders and firms to embrace ICT for risk
193 management if they want to achieve success. Adopting ICT can have substantial impact on project
194 risk management, assisting the delivery of quality projects safely and on budget and time.

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

205 **4. Survey of BIM-based MiCRM**

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

208 *4.1. Relationship between BIM and MiCRM*

209 BIM is both a game-changing, disruptive technology and a process. In fact, both BIM and MiC
210 are game-changing, disruptive technologies. Their integration therefore plays a weighty role in
211 transforming the AEC industry. As a technology, BIM assists project participants to visualize what
212 is to be constructed in a virtual environment to resolve any issues before the actual construction
213 [40], an integral part of risk management. BIM is a game-changing, disruptive technology, as it
214 markedly changes project processes via digital integration. From a process standpoint, Autodesk
215 [41] defines BIM as a process that starts by creating an intelligent 3D model and enables
216 simulation, document management, coordination, integration, communication, and collaboration
217 between project stakeholders.

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

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

233 *4.2. MiCRM through BIM used alone*

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

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

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

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

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

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

279 *4.3. MiCRM through BIM used alongside STTs*

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

282 *4.3.1. BIM+RFID*

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

287 The need to integrate BIM with RFID to improve MiC delivery efficiency is recognized. Li et
288 al. [11] proposed an RFID-enabled BIM platform to improve the schedule performance of MiC.
289 Smart construction objects (SCOs) enabled by IoT and cloud technology were developed along
290 with an RFID-enabled gateway for managing the SCOs. A BIM platform was established for real-
291 time decision-making. Zhai et al. [8] replicated Li et al. [11]'s effort with some improvements.
292 One of which being using smart-trinity-tag consisting of RFID tags, QR codes, and NFC tags
293 instead of using only RFID tags in their developed IoT-BIM platform. Such approach helps reduce
294 the chance of losing information because of failure of one tag type. Using BIM to help onsite

295 modules assembly has several benefits, e.g., providing a useful tool to manage physical and digital
296 presentations [12]. However, with lack of real-time visibility and traceability, and inefficient data
297 exchange, these benefits cannot be fully achieved. Li et al. [12] reported a platform based on IoT-
298 BIM-RFID-cloud-VR integration to solve these issues. Similarly, Zhong et al. [63] explored an
299 IoT-RFID-BIM platform for real-time visibility and traceability of modules manufacturing,
300 transportation, and assembly. All above-mentioned studies focused on information visibility and
301 traceability for monitoring project progress in real-time.

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

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

317 4.3.2. *BIM+GIS*

318 While BIM provides process and product data, GIS provides geospatial data. Hence, integrating
319 BIM and GIS is an effective way to introduce geospatial context into MiC design and construction
320 [71]. This leads to safer, smarter, and resilient modular buildings, and reduced risk due to improved
321 efficiency and prevention of critical data losses in various project phases [72]. By GIS data
322 introducing geospatial elements into BIM models, MiC projects can be better designed and built
323 within the context of their real-world surroundings.

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

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

340 *4.4. MiCRM through BIM used alongside 3D-MCCTs*

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

343 *4.4.1. BIM+3D laser scanning*

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

356 Some studies, instead, focused on quality control and tolerance analysis. Kalasapudi and Tang
357 [83] developed a framework integrating laser scanning with BIM for detecting and analyzing fit-
358 up problems in curved MiC units. A tolerance network provided a quality control framework for
359 adaptive redistribution of manufacturing and installation errors to resolve fit-up problems in MiC.
360 The risks of misalignments and inefficient tolerance analysis remained the focus in this case [84].

361 Though useful, current applications have limitations. They primarily focus on two issues:
362 geometric quality assessment (GQA) and geometric quality control (GQC). GQA has seen most
363 existing studies, where dimensional quality assessment is the main focus. Recent reviews [85,86]

364 showed that concerning GQA, laser-scanned point-clouds can be used for three purposes –
365 dimensional, deformation/deflection, and surface quality assessments. Deformation/deflection and
366 surface quality assessments remain to be sufficiently explored with BIM-laser scanning integration
367 in MiC realm. The foci of research on dimensional quality assessment include the sizes, shapes,
368 positions, etc. of MiC objects. More future studies on positioning are needed. Extant research using
369 BIM-laser scanning integration for GQA/GQC in MiC further focus more on four-sided shaped
370 and flat-surfaced objects (e.g., rectangular objects) for convenience. Though complex geometries,
371 like cylindrical and interwoven ones, pose greater challenges to quality assurance in MiC [83],
372 they are largely overlooked, representing a promising direction for future research. BIM-laser
373 scanning integration holds promise for not only automated QA/QC, but also several other problems
374 throughout a project – building renovation, safety management, heritage applications, etc. [85] –
375 which have received limited attention in BIM-laser scanning-based studies in MiC field.

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

386 techniques. Data preprocessing to eliminate noise can improve scan data quality. More BIM-laser
387 scanning-based techniques addressing above issues [76] must be developed to improve MiCRM.

388 *4.4.2. BIM+photogrammetry*

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

398 The field needs further studies applying BIM-photogrammetry integration to MiCRM. In this
399 future research direction, BIM-photogrammetry-laser scanning integration implementation is still
400 recommended because photogrammetry has shortcomings. For example, it is easily affected by
401 darkness. This can be overcome by laser scanning albeit it also has limitations photogrammetry
402 can overcome. Therefore, photogrammetry and laser scanning are viewed as complementary
403 technologies whose integration “can lead to more accurate and complete products” [89]. There are
404 three types of laser scanners: terrestrial, airborne, and mobile laser scanners [86]. Whereas current
405 applications of BIM-photogrammetry-laser scanning integration have typically used terrestrial
406 laser scanners where scan data acquisition necessitates manual movement of the scanner to
407 different locations, future research could employ airborne or vehicle-borne laser scanners for
408 deeper automation of data acquisition. It could also employ aerial photogrammetry and/or close-

409 range photogrammetry [90]. The former assisted by an aircraft or a drone is recommended in
410 situations, such as upper-level exteriors of high-rise modular buildings, where it may be difficult
411 or dangerous to use the latter assisted by humans.

412 4.4.3. BIM+AR

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

422 However, there is still limited research investigating using BIM-AR integration in MiC to
423 identify potential problems, tackle risks, and improve tasks efficiency. A real-time 4D BIM-based
424 AR system for MiC progress monitoring has only recently been invented by Lin et al. [93]. This
425 system compares as-designed AR models with as-built sites and has a markerless AR registration
426 method for linking 4D BIM data with as-built ones. It helps avoid modules assembly errors through
427 offering a helpful tool for assembly schedule control and sequence monitoring. Tang et al. [94]
428 developed a workflow for BIM-AR-based MiC design visualization and installation to allay risks
429 such as "unreasonable design". BIM-AR application in MiC deserves more exploration. Such
430 works would be more effective when BIM-AR integration is executed alongside STTs like RFID
431 (Section 4.3.1) [91]. A reason is that although 3D-MCCTs help capture/analyze data from the real

432 environment, they do not enable objects to be smart in regard to communicativeness, autonomy,
433 and awareness for enhancing MiC efficiency [19].

434 *4.4.4. BIM+VR*

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

454 *4.5. Other applications*

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

457 *4.5.1. BIM+simulation+optimization*

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

466 *4.5.2. BIM+SWT*

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

472 *4.5.3. BIM+context-aware cloud computing*

473 Abedi et al. [60] identified the major risks in MiC supply chain, including poor coordination,
474 improper planning and scheduling, wrong modules deliveries, lack of integration, poor production
475 timing, poor control and supervision, and poor communication between stakeholders. A context-
476 aware cloud computing BIM prototype was created for MiC supply chain management to mitigate

477 these risks. After surveying existing research, the following Section 5 discusses findings and future
478 research needs.

479 **5. Discussion and future needs**

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

496 **< Please insert Table 2 around here >**

497 *Planning and design risks.* These risks occur very early in the project and if unmanaged, can
498 cause more risks in the project later. Design errors (PD1) should not be tolerated in MiC because,
499 unlike in traditional construction, in MiC, it is highly difficult to make any design changes (PD2)

500 later in the project, especially in the onsite assembly phase where the modules have already been
501 manufactured and transported for installation. And during modules manufacturing, fixing PD1 can
502 be costly and time-consuming, adversely impacting project cost and schedule. PD1 can also cause
503 several other risks such as inefficient (e.g., delays in) design approval process (PD12), inaccurate
504 quantities takeoff and cost estimation (PD8), and manufacturing errors (M2) (in the manufacturing
505 phase). Automating MiC design with BIM is an effective strategy to eliminate PD1. BIM allows
506 automatic, instead of manual, review of MiC designs to discover and repair any errors (overlapping
507 geometries, etc.) before approving shop drawings for modules manufacturing. Moreover, using
508 BIM, shop drawings can be created without the need for cross-coordination and detailed checking
509 between numerous drawings [50], managing the risk of long design hours (PD5). Another benefit
510 of BIM automation of MiC design is that as BIM is an object-based parametric design technology,
511 throughout the design process, PD2 can easily be managed because once an object is modified, all
512 other related objects are also automatically modified.

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

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

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

543 It is identified in Section 4 and Table 2 that for MiCRM, BIM can be used alone or alongside
544 other digital technologies, namely STTs and 3D-MCCTs. This survey is conducted to understand

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

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

568 < **Please insert Fig. 3 around here**>

569 *5.1. BIM-based MiCRM software*

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

587 < **Please insert Fig. 4 around here**>

588 *5.2. Fully automated and practical BIM-based MiCRM systems*

589 The second recommendation is two-fold. The first fold deals with developing fully automated
590 BIM-based MiCRM systems. Previous studies claimed that manual handling is time-consuming

591 and error-prone and therefore can significantly reduce efficiency in practice, a major justification
592 for their development of BIM-based automated systems for MiCRM. It is thus interesting to
593 observe that most of the developed systems still necessitate substantial manual handling in their
594 implementation. In Liu et al. [43]’s study, “part of the simulation network still needs to be
595 established manually.” To enhance the performance of existing systems, future research should
596 develop fully automated systems. Where full automation cannot be achieved, the possibility of
597 developing systems that can detect and/or rectify human errors as they occur could be explored.
598 Without these, manual handling and human errors may continue to limit efforts to improve industry
599 practice through automation.

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

608 *5.3. A holistic BIM-based MiCRM approach*

609 The third recommendation is about adopting a holistic approach to BIM-based MiCRM. As
610 Fig. 4 shows, BIM has six dimensions ranging from 3D to 8D. Existing BIM-based MiCRM
611 research pays much attention to the first three Ds (visualization, scheduling, and cost estimation),
612 while paying limited attention to facilities management, sustainability, and safety risks.
613 Visualization, scheduling, and cost estimation are all performed in project planning and design

614 phase, and the substantial focus on this phase, as identified in Section 4.2, explains why schedule-
615 and cost-associated risks have received much attention. There remain limited studies applying BIM
616 to manage risks in facilities management phase of MiC projects. This may be attributed to the
617 perception that the areas wherein MiC has caused *significant* disruption are design, manufacturing,
618 logistics, and onsite construction, hence attention might have been biased toward other areas.
619 Further studies are also needed to utilize BIM to enhance MiC projects sustainability and safety.
620 One suggestion is to analyze how BIM can be used to monitor workers safety during installation
621 of the heavy/bulky modules. It is commonly understood that MiC is surely a sustainable approach,
622 as it reduces the impact of construction on the environment by waste, noise, and dust reduction.
623 This understanding may be a contributing factor in the partial focus on sustainability risks. It
624 should not be overlooked that sustainability is not just about waste, noise, and dust reduction. It
625 covers other broader issues, e.g., CO₂ emissions. A holistic BIM-based MiCRM approach is
626 needed to tackle the complete world of risks, to significantly improve the chance of MiC project
627 success.

628 *5.4. An industry 4.0-DfMA-multidisciplinary-interdisciplinary system-thinking*

629 The fourth recommendation concerns embedding the concept of *industry 4.0-DfMA-*
630 *multidisciplinary-interdisciplinary system-thinking* in the research and practice of BIM-based
631 MiCRM. Zou et al. [20] suggested to implant a multidisciplinary system-thinking into the research
632 and practice of BIM-based risk management in traditional construction. However, the system-
633 thinking required for BIM-based MiCRM is much more than just a multidisciplinary one. Here,
634 *an industry 4.0-DfMA-multidisciplinary-interdisciplinary system-thinking* is required. Industry 4.0
635 is upon the AEC industry, demanding it to transform through digitization, robotization,
636 automatization, and additive manufacturing. BIM and BIM-related technologies help the industry

637 to digitize and integrate vertical and horizontal value chains [101]. As for MiC, it moves
638 construction tasks to manufacturing environment wherein high-level automation and robotics can
639 be applied. By so doing, it naturally brings together experts with multidisciplinary and
640 interdisciplinary background to complete the project. Also, MiC is a DfMA (design for
641 manufacture and assembly) technology, meaning DfMA principles [102] must be followed to
642 mitigate risks. From above discussion, it is clear that the concept of *industry 4.0-DfMA-*
643 *multidisciplinary-interdisciplinary system-thinking* must be embedded in the research and practice
644 of BIM-based MiCRM. Addressing this recommendation is important to ensure that necessary
645 knowledge, skills and expertise are employed for effective BIM-based MiCRM, which is critical
646 to the success of MiC projects.

647 *5.5. BIM-automatic rule checking integration for MiCRM*

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

659 *5.6. BIM-cybersecurity-blockchain integration for MiCRM*

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

668 **6. Conclusions**

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

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

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

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

702 **Declaration of interests**

703 None.

704 **Acknowledgments**

705 This research is fully funded by the Chinese National Engineering Research Centre for Steel
706 Construction (Hong Kong Branch) at The Hong Kong Polytechnic University (Grant number: 1-
707 BBV5). We are extremely grateful to the Editors and Reviewers whose constructive and invaluable
708 comments and suggestions helped improve the quality of this paper significantly.

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 998

999 **Table 1**

1000 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”

1001

1002 **Table 2**

1003 **Potential MiC project risks and their corresponding BIM-based risk management strategies identified from literature.**

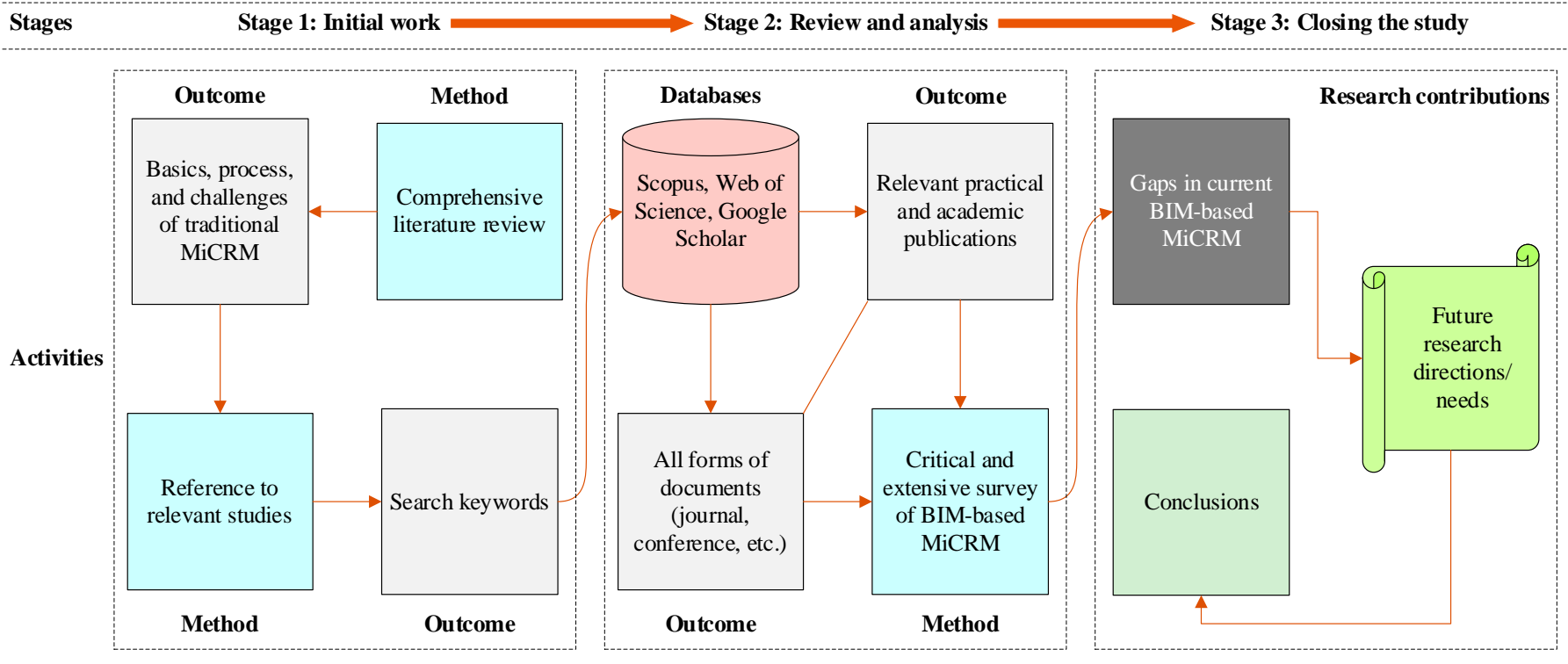
Risk categories	Code	Risk factors	BIM-based risk management strategies	Key references
Planning and design risks	PD1	Design errors	BIM automation of MiC design	[14,50]
		Design changes	BIM automation of MiC design BIM-RFID integration for efficient communication among stakeholders BIM-RFID integration 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
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	[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	[11,59,69]
			BIM-RFID integration to achieve JIT delivery of modules to site	
	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	[57,58,97]
			BIM-improved genetic algorithm integration for assembly sequence planning and optimization	
	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]

Multi-phase risks	MS1	Inefficient verification of modules due to ambiguous labels	BIM-AR integration for modules assembly schedule control and sequence monitoring	
	MS2	Inaccurate as-built/as-is dimensions estimation	BIM-RFID integration for efficient identification and verification of modules	[11]
Universal risks	U1	Poor communication between stakeholders	BIM-laser scanning integration for accurate dimensions estimation	[76–82]
			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]

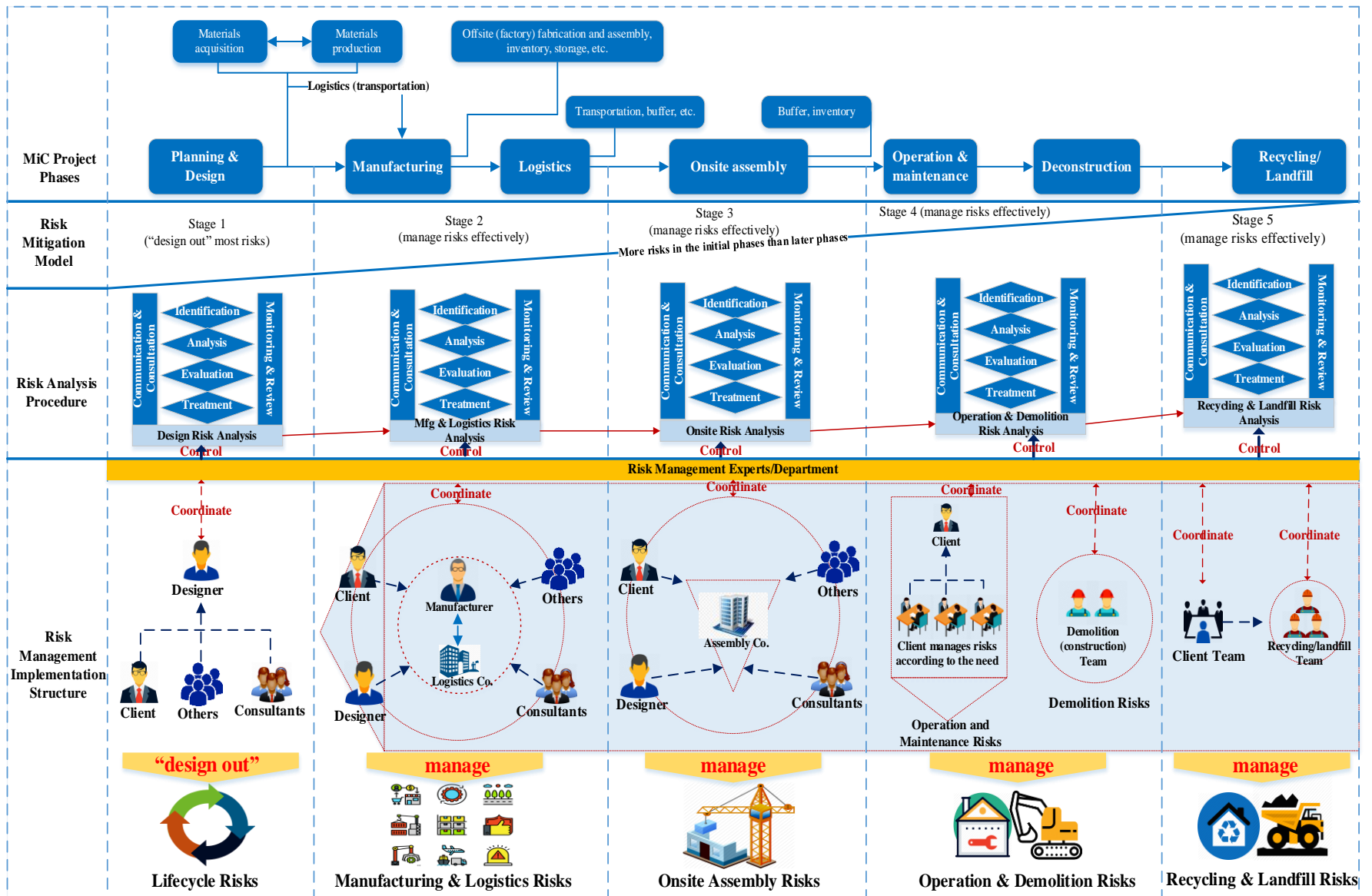
1004 Note: MiC = modular integrated construction; BIM = building information modeling; SWT = semantic web technologies; CCT = cloud computing technology; GIS = geographic
 1005 information system; JIT = just-in-time; PSOT = particle swarm optimization technology; RFID = radio-frequency identification; ERP = enterprise resource planning; IoT = the
 1006 internet of things; AR = augmented reality; VR = virtual reality.

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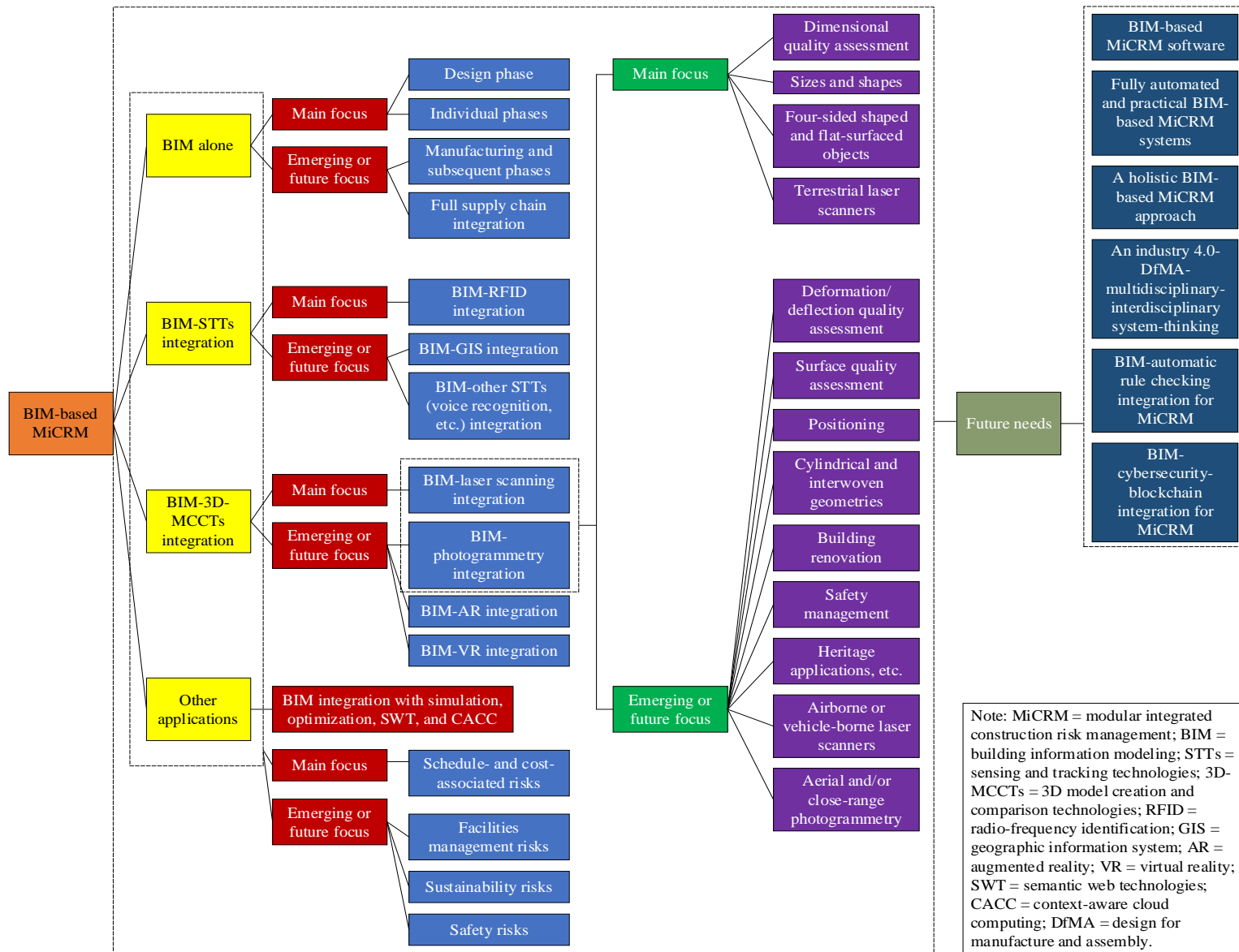
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1009 **Fig. 1.** Overview of research approach.



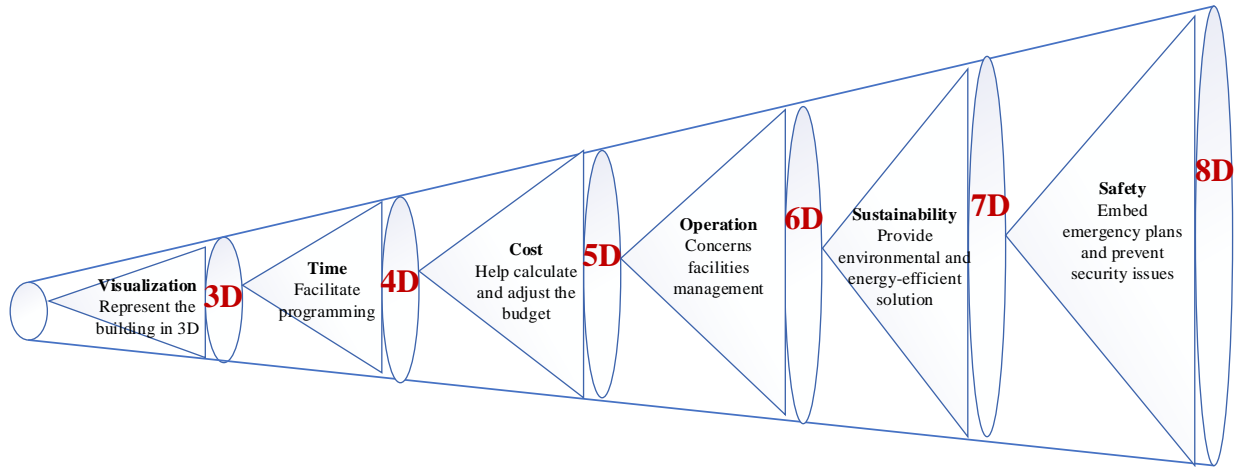
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Fig. 2. Generic MiCRM framework. Adapted from Zou et al. [20] with MiC features integrated.



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Fig. 3. Summary of findings.



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1017 **Fig. 4.** BIM dimensions.