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REVIEW

Strategies for Maximising the Value of Digital Twins for Bridge Management and Structural Monitoring: A Systematic Review

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Abstract

Building Information Modelling (BIM) extends its utility to infrastructure management during the operational phase and can evolve into a Digital Twin (DT) when coupled with specific technologies or systems. In Engineering, Construction, and Operations (EC&O), BIM and DTs are strongly interconnected research topics. Especially for bridges, this relationship is represented by Bridge Information Modelling (BrIM) and Bridge Digital Twin (BDT). However, while this connection is recognised, it lacks developments regarding modelling strategies or data flow and integration. Therefore, the purpose of this study is to conduct a review of the current state of BrIM as an extension of BIM and its relationship with BDT, encompassing strategies for creating BrIM models of existing bridge assets. Additionally, it will explore integrating technologies or systems for structural performance monitoring and management (SPMM) to form BDTs. A systematic review was conducted using PRISMA protocol. Of the 3459 articles that were initially retrieved from a query of academic databases, 152 were assessed and classified manually, and 128 of these were selected for full content review. Analysis of the selected articles demonstrated the growing value of BDTs in SPMM of bridges, evolving from BrIM. Along with release of IFC4.3, BrIM development initiatives include IFC entity extension, IFC property sets usage, ontology development, and OpenBrIM implementation. Point cloud approaches are the most prevalent among different as-is BrIM modelling techniques, while parametric and data-driven approaches are gaining traction. Key challenges to BDT adoption, with respect to technological integration include interoperability, real-time performance, model updates, cost, and skill gaps.

1 Introduction

The emergence of digital technology has transformed the different phases of the infrastructure lifecycle. Building Information Modelling (BIM) has become a key tool in revolutionising building design, construction, and management [1–4]. Currently, its effects extend beyond vertical structures, with notable advancements in horizontal infrastructure, particularly bridges, where it is gaining a wider acceptance [5, 6]. The recent approval and accreditation of IFC 4.3 by the International Organization for Standardization (ISO) (ISO 16739-1:2024) [7] highlights this progress, as it includes bridges and most other types of infrastructure [8]. These advancements are relevant milestones in the evolution of bridge structural performance monitoring and management (SPMM), enabled by two leading technologies: (i) Bridge Information Modelling (BrIM); and (ii) Bridge Digital Twin (BDT). BrIM is a branch of BIM tailored for bridges [9–12], representing a considerable extension of the broader BIM technology. The phrase "Bridge Information Modelling" is non-standardised, so it might be interpreted as only referring to BIM for bridges.

Since the 2000s, when BIM gained popularity, efforts have been made to develop an equivalent bridge technology [13–15]. For example, in 2006, a pilot study targeted at developing and evaluating a 3D-centric model for an integrated design and construction process for highway bridges was published by the National Cooperative Highway

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Research Programme (NCHRP) in the United States of America (USA) [13]. In 2009, Shirole et al. [16] identified the major concerns and obstacles to introducing BrIM in the construction industry, highlighting fundamental distinctions from BIM.

Around 2015, OpenBrIM was established to promote bridge model interoperability. Originally, it was an independent initiative with no formal link to BIM, but it soon evolved to attempt the integration of BrIM with existing BIM schemes and standards [13, 15]. As global interest in using BIM for infrastructure increased [17], significant advancements were made from 2018 onwards. These were reflected in parallel projects managed by buildingSMART International (bSI) [18], which aimed to expand the scope of Industry Foundation Classes (IFC) to other infrastructure domains beyond buildings. The IFC was extended with the contributions of these projects, resulting in the publication of IFC 4.3, which includes bridges. Recently, due to trademark aspects, there have been attempts to adopt the term "BIM for bridges" instead of "BrIM" [13]. It is noteworthy that BrIM, now gaining acceptance, was slower to develop than its parent BIM, which has long been included in commercial software. This delayed progress was mostly due to significant hurdles, such as a lack of standardisation [13].

Along with that, BDT, which is part of the broader Digital Twins (DTs) concept, have become a hot topic in Engineering, Construction, and Operations (EC&O) [19–21]. Unlike BIM and BrIM, the use of DTs in this industry lacks standardisation [22, 23]. Nonetheless, there have been attempts to overcome this barrier. For example, the question of definition, which has been widely raised [23, 24], seems to be gradually addressed. In addition to the ISO/IEC 30173 standard [25], published in 2023, which introduces terminologies for various sectors, including buildings and civil infrastructure, researchers have been proposing specific definitions of DT (see, for instance, [26] and [27]). As with the general relationship between DT and BIM [22], BDT is hardly separable from BrIM [28]. In the current trend, as illustrated in Fig. 1, these two last technologies are being explored and investigated to address the following challenges:

(a) Developing interoperable digital models of existing bridges that comply with BIM schemas adapted for horizontal-development structures;
(b) Implementing global BIM methodologies tailored to bridge projects, promoting collaboration among project managers, owners, structural engineers, contractors, and maintenance teams; and
(c) Integrating structural health monitoring (SHM) systems with BrIM and other advanced technologies and tools. These include the Internet of Things (IoT), Artificial Intelligence (AI)/Machine Learning (ML), Cloud Computing, Virtual Reality (VR)/Augmented Reality (AR)/Mixed Reality (MR), and 5G Wireless, which together enhance SPMM of bridge infrastructures.

In the challenge (a) mentioned above, the recent ISO approval and accreditation of the IFC 4.3 scheme has significantly advanced interoperability within BrIM. Before the release of this last version, several relevant transportation infrastructure entities were absent from the IFC schema. Still, ongoing discussions have raised questions on whether this version adequately covers all bridge components.

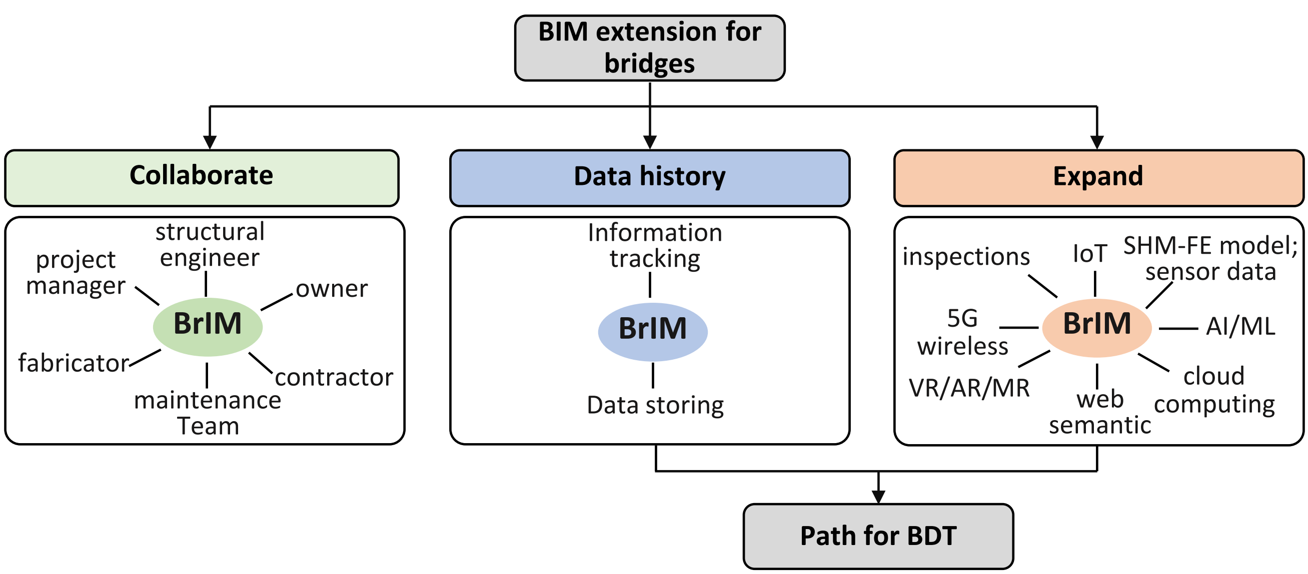

Fig. 1 Overview of the current trend of BrIM and its connection towards BDT

Therefore, the usage of IFC property sets and ontology models, for example, is being investigated to ensure full information exchange [15, 29–35]. However, as noted by Costin and Muller [15], modelling these ontologies presents challenges, particularly because, in practice, software developers and industry experts may not progress at the same pace. Within BrIM, a key focus has been the development of digital bridge models in open standard formats (OpenBIM). For existing bridge assets, approaches such as scan-to-BIM (based on laser scanning and photogrammetry) [6, 20, 31, 36] and parametric reconstruction from 2D sketches [37–39] are part of the strategies employed. Nevertheless, challenges remain regarding the most appropriate strategy due to unclear advantages and scope within the OpenBIM context.

For challenge (b), unlike the broader BIM, which has seen widespread implementation in industry and government sectors and has even become mandatory in some regions [40, 41], evidence of BrIM application in the real-world is limited. However, with the official inclusion of BrIM into the BIM framework, bridge projects are expected to employ the same procedures as buildings. It raises the question of whether the term BrIM will continue to be used or be referred to as "BIM for bridges" or if the generic term "BIM" will become the norm.

Lastly, for challenge (c), similar to its parent BIM, BrIM is currently the subject of debate and implementation initiatives centred on semantic enrichment, IoT integration, and semantic web integration [31]. It is unclear whether these implementations are taking place beyond academic initiatives or if the essential conditions have been created to do so. For example, the current IFC version 4.3 lacks object classes for anomalies typically required in SPMM. Furthermore, there has been a reported shortage of unified platforms that combine diverse technologies to build a functional BDT [6].

To address the current state-of-the-art and elucidate the points raised in (a), (b), and (c), this systematic literature review (SLR) focuses on the following research questions (RQs), divided into two parts, namely:

- **Part 1:** BIM capabilities and extensions for BrIM:
  - RQ1: What is the current state of BrIM in relation to its origin from BIM?
  - RQ2: What are the strategies for generating BrIM models of existing assets, and what are the limitations and challenges?
- **Part 2:** From BrIM to BDT for SPMM:
  - RQ3: What is the current state-of-the-art with respect to integrating BrIM with technologies or methodologies for SPMM to create (BDTs)?

This review is structured as follows: after this introduction, Sect. 2 presents the research methodology, which is subdivided into search strategy, bibliometric analysis methodology, and content analysis methodology. Sect. 3 provides the bibliometric analysis and Sect. 4 conducts a content analysis to address the established RQs. Finally, the conclusions are presented in Sect. 5.

2 Research Methodology

2.1 Overview

A Systematic Literature Review (SLR) was conducted to assess the current state-of-the-art concerning the strategies involved in developing BrIM models as a subset of BIM and the development of BDT from this basis, specifically targeting SPMM. This SLR is based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [42], which allow for a systematic and rigorous selection of source material [43]. The procedure ensures that only the most relevant literature is included, prevents bias in source selection, creates transparency for future researchers, and highlights what is known and unknown about the topic under examination [26].

This SLR was complemented by a bibliometric analysis, which is increasingly employed by several researchers [44]. The analysis is used to identify the scientific framework, conceptual structures, dynamics, and paradigm shifts in the reviewed studies. This framework's methodology was divided into the following subparts: (i) Search Strategy; (ii) Bibliometric Analysis; and (ii) Content Analysis.

2.2 Search Strategy

Following the PRISMA 2020 guidelines, after formulating the RQs in Sect. 1, the search strategy involved four main stages: (i) identification of articles in relevant journal databases based on strategically defined keywords; (ii) screening; (iii) eligibility to select the final articles for the review process; and (iv) inclusion entailing the final selected articles. The two significant databases for scientific research, Scopus and Web of Science (WoS), were used for this review. Both databases are comprehensive and are among the most widely used by researchers [45–47].

The search used the "article title/abstract/keyword" field. Preliminary studies and searches using broad terms facilitated the definition of keywords and keyword combinations. These combinations, as well as the records found, are presented in Tables 1 and 2. As shown in these tables, 15 keyword combinations were created and grouped into the following four sets:

- KWG 1 AND KWG 2: Expected to collect articles dealing with BrIM or BIM for bridges;

Table 1 Aggregated list of search keywords

Keyword groups (KWG)	KWG 1: Bridges	KWG 2: BrIM/BIM for bridges	KWG 3: DTs	KWG 4: BrIM modelling strategies	KWG 5: BIM to BrIM extension/ expansion	KWG 6: BDT for bridge SPMM
Keywords	Bridge*	"Building information model*"; BIM; BrIM	"Digital twin*"; "internet of things"; IoT	"Laser scan*"; "unmanned aerial vehicle*"; "unmanned aircraft system"; drone; photogrammetry; "point cloud"; point-cloud; data-driven; parametri*; "digital model"; "3D model"; "3D bridge model"; "2D model"; "2D drawing"; as-built; "as built"	"IFC extension"; "IFC standard"; IfcBridge; "IfcRail"; Ontology; Interoperability	"Structural health monitoring"; SHM; "finite element"; FEA; sensor*; sensing; anomal*; inspection; maintenance; management; real-time

- KWG 1 AND KWG 4: Expected to collect articles on current strategies for the digitalisation of existing bridge assets;
- KWG1 AND KWG2 AND KWG5: Expected to collect articles on the current approaches about BIM extension/ expansion to bridges, directly related to IFC issues;
- KWG 1 AND KWG 2 AND KWG 3 AND KWG 6: Expected to collect articles about BDT creation from BIM or BrIM aimed at bridge SPMM.

The selection process went through the following inclusion criteria:

- **Publication Year:** 2016 to 2024;
- **Subject Area:** Engineering and computer science;
- **Document Type:** Articles and review articles;
- **Source Type:** Journals;
- **Language:** English;
- **Others:** Publication stage limited to "final"; Relevance and relationship with the topic.

The full search queries were performed on June 7, 2024, considering the period between 2016 and 2024. 2016 was chosen as the starting year, taking into account that publications on DT in the built environment, in general, and bridges, in particular, were significantly reduced until this year (see, for instance, [19, 28, 44]). Since DT for bridges is one of the central themes of this research, articles published before 2016 were not considered relevant. The first search returned 3,459 results, which were reduced to 605 after applying the aforementioned inclusion criterion (before removing duplicates). The removal of duplicates involved two steps: automatically from the results in search database platforms, followed by merging remaining records into an Excel sheet, and manually identifying duplicates. In this process, 342 records were discarded, leaving 263 articles for further screening and eligibility assessment. The process resulted in the exclusion of 135 articles, leaving 128 articles for full content review (total included articles), as illustrated in Fig. 2.

2.3 Bibliometric Analysis Methodology

Van Eck and Waltman [48] define bibliometric analysis as a method used to map and visualise specific scientific studies within a knowledge domain. It is a quantitative approach by which substantial insights can be extracted from large data, such as identifying research trends, collaboration patterns, and evaluating literature structure [49–51]. As the information age has progressed, bibliometric analysis is increasingly used in many research domains [44]. Various software

Table 2 Keyword search combinations and results found in search databases

#	Keyword(s) 1	AND Keyword(s) 2	AND Keyword(s) 3	AND Keyword(s) 4	Records		
					Scopus	WoS	Total
KWG1 AND KWG3							
1	Bridge*	"Building information model*" OR BIM OR BrIM			1290	661	1951
KWG1 AND KWG4							
2	Bridge*	"Laser scan*"	"Digital model" OR "3D model*" OR "3D bridge model "		124	72	196
3	Bridge*	"Unmanned aerial vehicle*" OR drone OR "unmanned aircraft system"	"Digital model" OR "3D model*" OR "3D bridge model "		99	46	145
4	Bridge*	Photogrammetry	"Digital model" OR "3D model*" OR "3D bridge model "		102	60	162
5	Bridge*	"Point cloud" OR point-cloud	"Digital model" OR "3D model*" OR "3D bridge model "		130	71	201
6	Bridge*	Data-driven	"Digital model" OR "3D model*" OR "3D bridge model "		15	8	23
7	Bridge*	Parametri*	"Digital model" OR "3D model*" OR "3D bridge model "		104	43	147
8	Bridge*	"2D drawing" OR "2D model" OR as-built OR "as built"	"Digital model" OR "3D model*" OR "3D bridge model "		79	32	111
KWG1 AND KWG2 AND KWG5							
9	Bridge*	"building information model*" OR BIM OR BrIM	"IFC extension" OR "IFC standard" OR ontology OR interoperability OR ifcbridge OR ifcrail		121	65	186
KWG1 AND KWG2 AND KWG3 AND KWG6							
10	Bridge*	"building information model*" OR BIM OR BrIM	"Digital Twin*" OR DT* OR "internet of things" OR IoT	"Structural health monitoring" OR "SHM"	22	15	37
11	Bridge*	"building information model*" OR BIM OR BrIM	"Digital Twin*" OR DT* OR "internet of things" OR IoT	"Finite Element" OR "FEM" OR FEA	8	7	15
12	Bridge*	"building information model*" OR BIM OR BrIM	"Digital Twin*" OR DT* OR "internet of things" OR IoT	Sensor* OR sensing	34	21	55
13	Bridge*	"building information model*" OR BIM OR BrIM	"digital Twin*" OR DT* OR "internet of things" OR IoT	Anomal* OR damage	17	10	27
14	Bridge*	"building information model*" OR BIM OR BrIM	"Digital Twin*" OR DT* OR "internet of things" OR IoT	Inspection OR maintenance OR management	102	66	168
15	Bridge*	"building information model*" OR BIM OR BrIM	"Digital Twin*" OR DT* OR "internet of things" OR IoT	Real-time	22	13	35
Total					2269	1190	3459

packages have been used, including VOSviewer, BibExcel, CiteSpace, Bibliometrix, and Gephi [45, 52].

In this review, the bibliometric analysis is performed to complement the SLR and provide a comprehensive review of the current state of BrIM technology as a branch of BIM and the employment of these technologies to develop BDT aimed at SPMM. It includes digitisation strategies and other processes involved. Bibliometric analysis may be divided into two categories: (i) performance analysis and (ii) science mapping [53, 54]. The performance analysis provides a detailed overview of scientific production from multiple perspectives. On the other hand, science mapping is a visual representation that helps understand scientific knowledge within a determined research area by linking publications and drawing content-related conclusions [49–51].

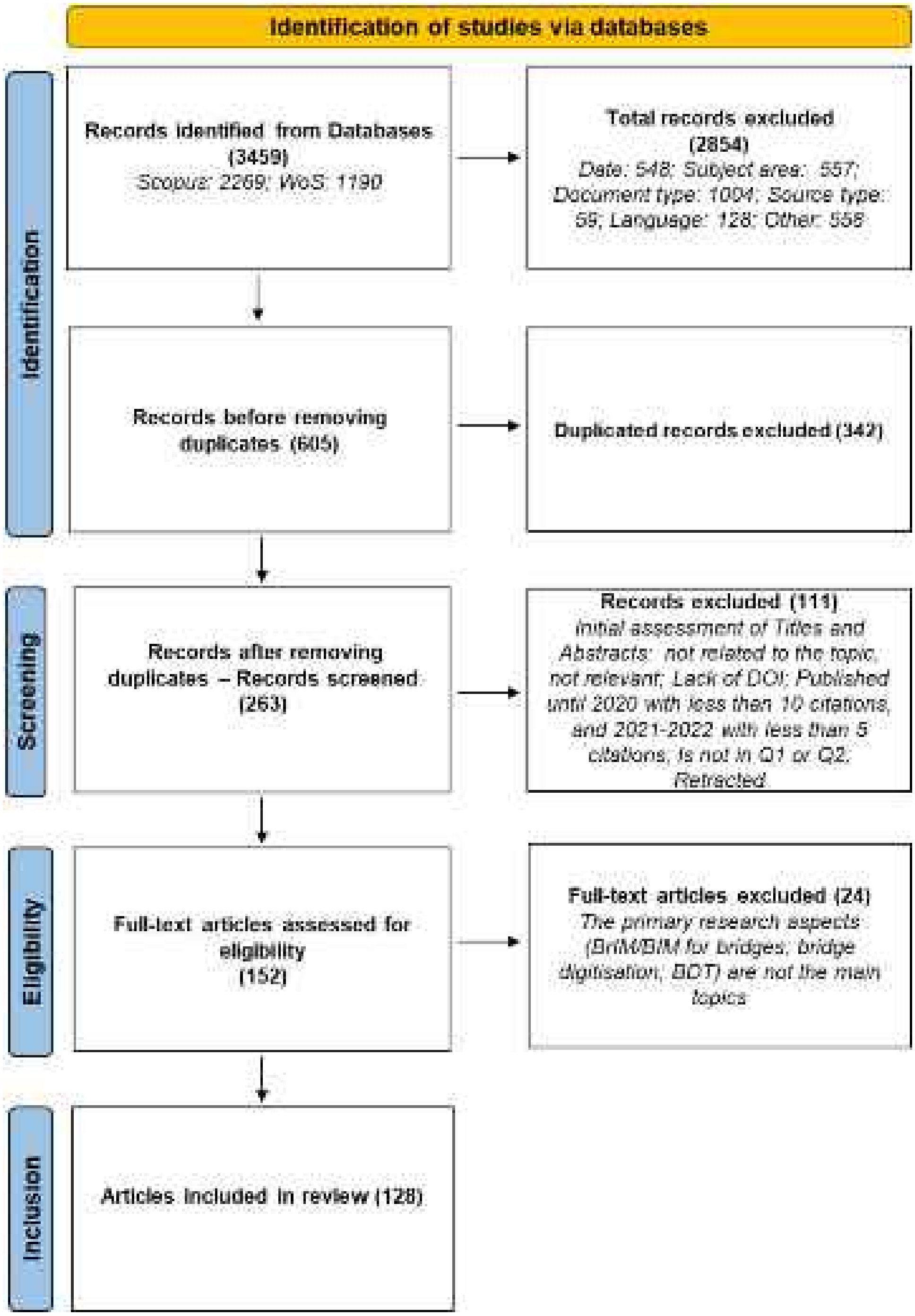

Fig. 2 The systematic review flowchart adopted for this study

In this review, performance analysis was carried out by sorting the selected records included in the study, and the science mapping was performed using the Bibliometrix and VOSviewer tools. The performance analysis is expressed in publications per year, most cited authors, most cited records, documents by country, and most used publication sources. Science mapping centres on analysing the word cloud, and co-occurrence relationships between keywords.

2.4 Content Analysis Methodology

This SLR analyses the identified studies from the following perspectives: (i) the current state of BrIM as a subset of BIM; (ii) current strategies for existing bridge assets digitisation; and (iii) the use of BrIM or BIM in developing BDT aimed at SPMM. Given the heterogeneity of the information collected from various studies, the systematic review was qualitatively summarised in a narrative synthesis, categorising the data into four primary themes: (i) From BIM to BrIM; (ii) BrIM models of existing bridge assets—digitisation strategies; (iii) Interoperability and semantic enrichment in BrIM; and (iv) From BrIM to BDT for SPMM.

3 Bibliometric Analysis

3.1 Performance Analysis

As outlined in the previous section, the article screening process has led to the inclusion of 128 papers in the study. Table 3 provides an overview of these papers, including the publication timespan (2016–2024), the number of sources (48), the average age of the articles (2.62 years), and the average number of citations per article (37.11). The average age of 2.62 years suggests that most articles were written within the past three years. As expected, most recent publications have fewer citations than older ones. This overview is complemented by a variety of data and data analysis performed both manually and automatically using Bibliometrix software (version 4.3.0) and the search databases used in this study (Scopus/WoS).

Figure 3 depicts the distribution of selected papers by publication year, which shows a notable increase in publications, albeit the growth is not linear. On the date the search was performed (June 7, 2024), the year 2023 had the most publications (32 articles). The year 2024, marked with an asterisk in the graph, had 24 selected articles, which suggests an increased number of publications on this topic by the end of 2024. Between 2016 and 2019, the number of articles per year was almost constant, with an average of 6.5. This number doubled in 2020, then slightly increased in 2021, and remained nearly constant until 2022, with an average of 16.5 articles per year. In 2023, this number doubled. As such, the six papers published in 2016, which remained nearly constant until 2019, increased nearly fivefold by 2023, demonstrating a considerable rise in studies involving the search keywords employed in this study.

Table 3 Overview of the characterisation of papers included in the studies for review

Feature	Quantification
Timespan	2016–2024
Sources	48
Documents	128
Annual Growth Rate	18.92%
Authors	445
Authors of single-authored docs	1
International Co-Authorship	35.16%
Co-Authors per Doc	4.2
Author's Keywords	442
References	7816
Document Average Age	2.62
Average citations per doc	37.11

DT technology for bridges and other infrastructures has recently become a highly researched and popular topic, which was not the case in the previous decade [45]. So, as one of the main search keywords, the significant rise in the number of articles is not surprising. DT technology is strongly related to other established technologies, systems, or processes such as BIM and SHM [55], as well as emerging or growing technologies (e.g., scan-to-BIM techniques, IoT, AI/ML, and VR/AR/MR), which are likewise experiencing an increase in publications.

Table 4 presents the characterisation of the selected publications in terms of document type and source (top 10 only), along with the SCImago Journal Rank (SJR) indicator for 2023, which measures the level of impact of a scientific journal. The SJR of these top ten journals spans from 0.508 to 2.626 (SJR > 0.5), encompassing both top-tier and moderately good journals [47]. About 62% (79 out of the 128 articles included in the study) are published in these top 10 journals, showing that these are the sources from which most of the articles were extracted. Within these top 10, Elsevier Ltd and the Multidisciplinary Digital Publishing Institute (MDPI) account for the majority of the articles, with 34 and 27 articles, respectively. Elsevier Ltd includes the following journals: "Automation in Construction", "Advanced Engineering Informatics", and "Advances in Engineering Software", and the MDPI includes "Applied Sciences", "Buildings", "Sensors", and "Sustainability".

Of the articles selected for review, the top 20 most cited articles, including titles and respective references, are shown in Table 5. The article authored by Ham et al. [56], titled "Visual monitoring of civil infrastructure systems via camera-equipped Unmanned Aerial Vehicles (UAVs): a review of related works" has received the most citations, a total of 401. In this set of the 20 most cited articles, about 75% are clearly related to inspection/SHM/structural assessment of bridges/transportation infrastructure/civil infrastructures, as indicated by their titles [17, 29, 33, 56–65]. Additionally, over 60% directly mention BIM/BrIM or aspects related to these technologies and/or DT technology [17, 29, 33, 61, 66–72]. This suggests that this portion of articles, as a sample, is relevant to the scope of this review. Approximately 55% of these articles include the use of reality capture/scan-to-BIM technologies/systems or processes, notably UAV/Unmanned Aircraft Systems (UAS)/Laser scanning/photogrammetry/point cloud [56–60, 63–65, 68, 70, 71]. Although alternative technologies/systems/techniques exist, this emphasises their involvement in processes related to BrIM and BDT for SPMM.

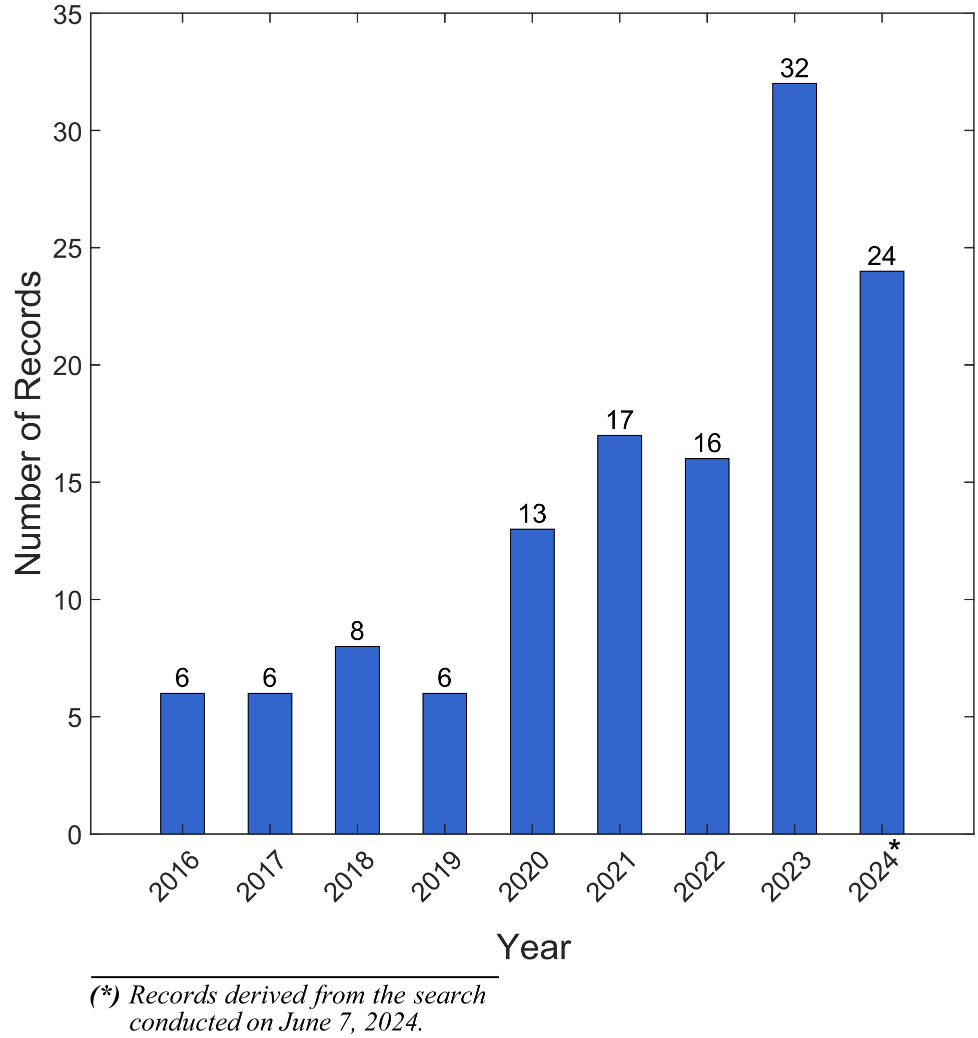

Fig. 3 Publication by year of the included studies

Table 4 Characteristics of included studies in terms of Document Type and distribution of studies based on the sources (top 10 sources)

Characteristic	Categories	Number of records
Document type	Journal article	113
	Review	15
Distribution of studies based on the sources (top 10)	Automation in Construction: $SJR_{2023} = 2.626$	23
	Applied Sciences: $SJR_{2023} = 0.508$	10
	Buildings: $SJR_{2023} = 0.575$	9
	Journal of Computing in Civil Engineering: $SJR_{2023} = 1.137$	7
	Advanced Engineering Informatics: $SJR_{2023} = 1.731$	7
	Structure and Infrastructure Engineering: $SJR_{2023} = 1.004$	7
	Advances in Engineering Software: $SJR_{2023} = 0.826$	4
	Journal of Civil Structural Health Monitoring: $SJR_{2023} = 1.087$	4
	Sensors: $SJR_{2023} = 0.786$	4
	Sustainability: $SJR_{2023} = 0.672$	4

Among the top 25 author keywords with the highest occurrence (Fig. 4), “building information modelling”, “bim”, “building information modeling (bim)”, “bridge inspection”, and “digital twin” are at the top (first 5). Other notable terms in this set include “bridge”, “point cloud”, “industry foundation classes (ifc)”, “maintenance”,

Table 5 First 20 most cited records (from articles included in study)

Ranking	Article Title	Year	References	Total citations
1	Visual monitoring of civil infrastructure systems via camera-equipped Unmanned Aerial Vehicles (UAVs): a review of related works	2016	Ham et al. [56]	401
2	Building Information Modeling (BIM) for transportation infrastructure—Literature review, applications, challenges, and recommendations	2018	Costin et al. [66]	319
3	Unmanned aerial vehicle inspection of the Placer River Trail Bridge through image-based 3D modelling	2018	Khaloo et al. [57]	164
4	Integration of BIM and GIS: Geometry from IFC to shapefile using open-source technology	2019	Zhu et al. [67]	157
5	Digital twinning of existing reinforced concrete bridges from labelled point clusters	2019	Lu and Brilakis [68]	155
6	Assessment of cracks on concrete bridges using image processing supported by laser scanning survey	2017	Valença et al. [58]	145
7	Framework for automated UAS-based structural condition assessment of bridges	2019	Morgenthal et al. [59]	139
8	Bridge inspection: human performance, unmanned aerial systems and automation	2018	Dorafshan and Maguire [60]	117
9	SeeBridge as next generation bridge inspection: Overview, Information Delivery Manual and Model View Definition	2018	Sacks et al. [17]	115
10	Integration of BIM and GIS: IFC geometry transformation to shapefile using enhanced open-source approach	2019	Zhu et al. [69]	114
11	Bridge Information Modeling for Inspection and Evaluation	2016	McGuire et al. [61]	102
12	Semi-automated generation of parametric BIM for steel structures based on terrestrial laser scanning data	2020	Yang et al. [70]	94
13	An Efficient Pipeline to Obtain 3D Model for HBIM and Structural Analysis Purposes from 3D Point Clouds	2020	Pepe et al. [71]	89
14	Bridge damage: Detection, IFC-based semantic enrichment and visualisation	2020	Isailović et al. [33]	88
15	Semantic Enrichment for Building Information Modeling: Procedure for Compiling Inference Rules and Operators for Complex Geometry	2017	Sacks et al. [72]	88
16	An information modeling framework for bridge monitoring	2017	Jeong et al. [62]	81
17	Streamlined bridge inspection system utilising unmanned aerial vehicles (UAVs) and machine learning	2020	Perry et al. [63]	80
18	Integrating RC Bridge Defect Information into BIM Models	2018	Hüthwohl et al. [29]	74
19	Automatic Crack Segmentation for UAV-Assisted Bridge Inspection	2020	Ayele et al. [64]	70
20	Modelling and strength evaluation of masonry bridges using terrestrial photogrammetry and finite elements	2016	Stavroulaki et al. [65]	64

"structural health monitoring"/"shm", "bridge information modelling", "damage detection", and "internet of things."

The most relevant authors, with three or more works included in this study, are shown in Fig. 5. Shim CS stands out with five articles. Three authors—Brilakis I, Li J, and Wang X, have four articles included each. Other 21 authors have three works included each.

Another notable detail related to the authors is the authors' local impact (within the set of articles selected for review), presented in Table 6 (top 10). For example, "Brilakis I" ranks first on this list, with four articles published and chosen within the scope of this study. Thus, the Number of Publications (NP) attributed to "Brilakis I" is 4. Each of these four articles has been cited at least four times, so the H-Index equals 4. The total citations (TC) for these four articles amount to 407 (TC = 407), with the earliest published in 2017 (PY-start = 2017), where PY stands for "publication year". Additionally, the M-Index attributed to "Brilakis I" is 0.5, which is calculated according to the relation H-Index/n, where n represents the number of years since the first published paper. The following authors are Shim CS (H-Index = 4, M-Index = 0.5, TC = 131, NP = 5, and PY-start = 2017), and Wang X (H-Index = 4, M-Index = 0.667, TC = 327, NP = 4, and PY-start = 2019) taking the second and third positions, respectively.

Regarding geographical distribution, Fig. 6a depicts the top ten countries with the highest concentration of authorship of the included papers as measured by the first author's affiliation. China ranks first with 28 articles, followed by the United States in second position (23 articles), and South Korea and the United Kingdom with 17 articles, taking the third position. In addition, a global map of the scientific production of these included studies is shown in Fig. 6b. This map reflects the total number of publications where at least

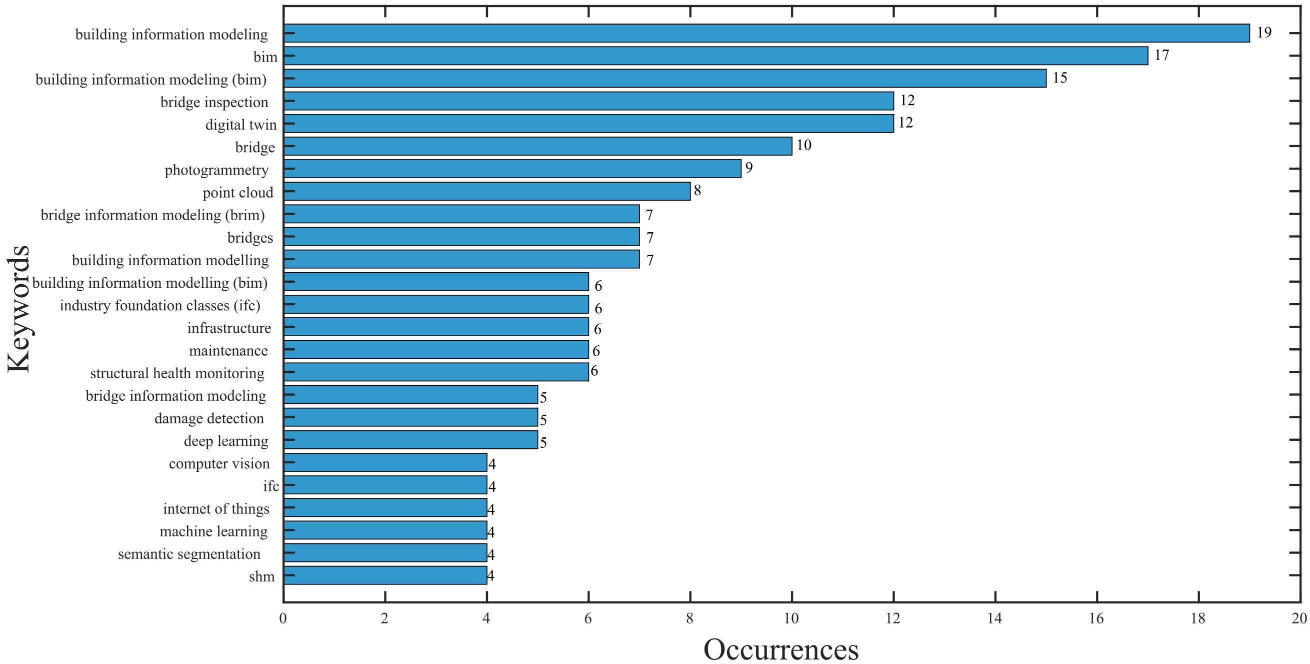

Fig. 4 Authors' keywords with the most occurrences (top 25)

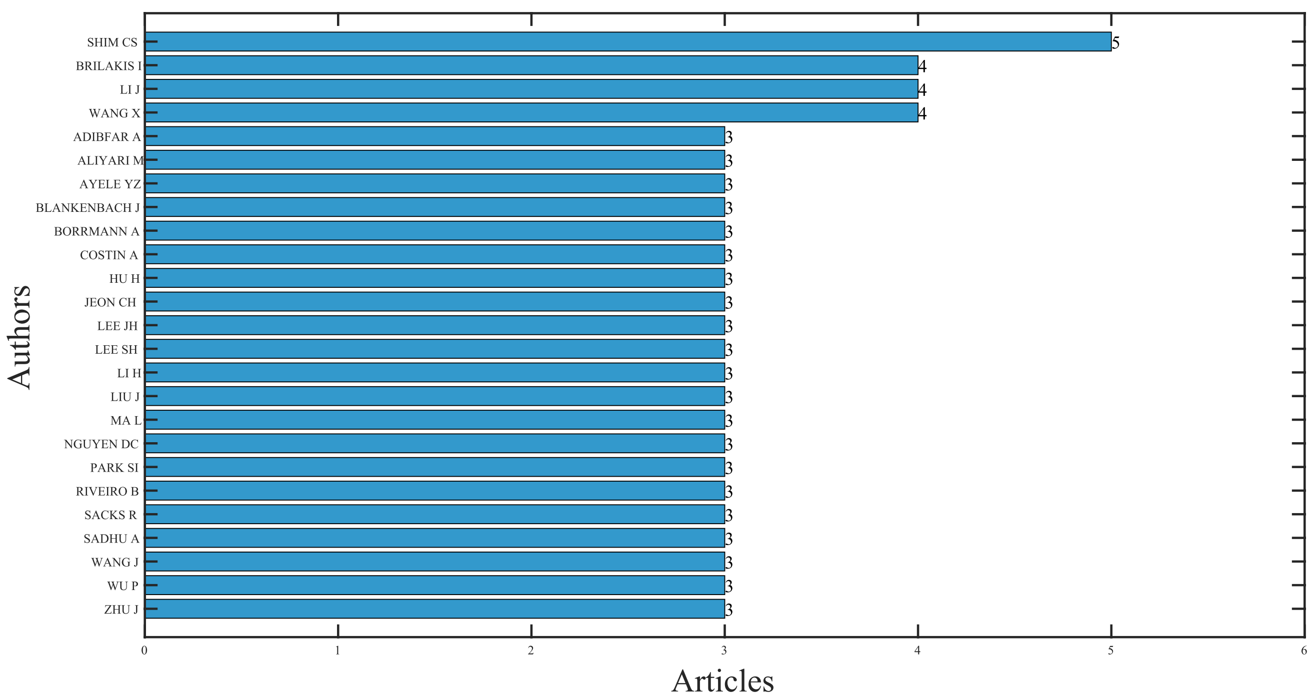

Fig. 5 Authors with most publications included in the study

one author is affiliated with a given country, regardless of the authorship role. The increasingly intense blue on the map corresponds to regions with the highest scientific production. The maximum publication frequency observed is 52, representing the highest concentration of scientific production.

3.2 Science Mapping

Science mapping is represented in word cloud (Fig. 7) and keyword co-occurrence (Fig. 8). The word cloud, generated using Bibliometrix software (version 4.3.0), displays

Table 6 Top 10 Authors' Local Impact (from articles included in the study)

Ranking	Author	H-index	M-index	TC	NP	PY-start
1	Brilakis I	4	0.5	407	4	2017
2	Shim CS	4	0.5	131	5	2017
3	Wang X	4	0.667	327	4	2019
4	Aliyari M	3	0.6	118	3	2020
5	Ayele YZ	3	0.6	118	3	2020
6	Borrmann A	3	0.375	288	3	2017
7	Hu H	3	0.429	362	3	2018
8	Jeon CH	3	1	51	3	2022
9	Lee SH	3	0.429	60	3	2018
10	Nguyen DC	3	1	51	3	2022

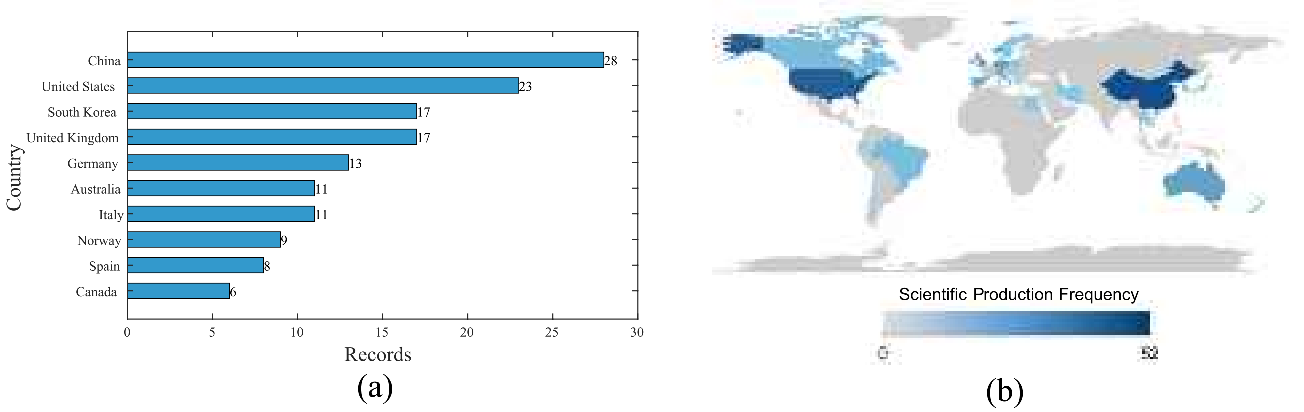

Fig. 6 Distribution of included studies per region in terms of article authorship: **a** Top 10 countries—first author's affiliation; **b** Global map—scientific production frequency

Fig. 7 Word cloud visualisation of the 50 most frequent terms within the included studies

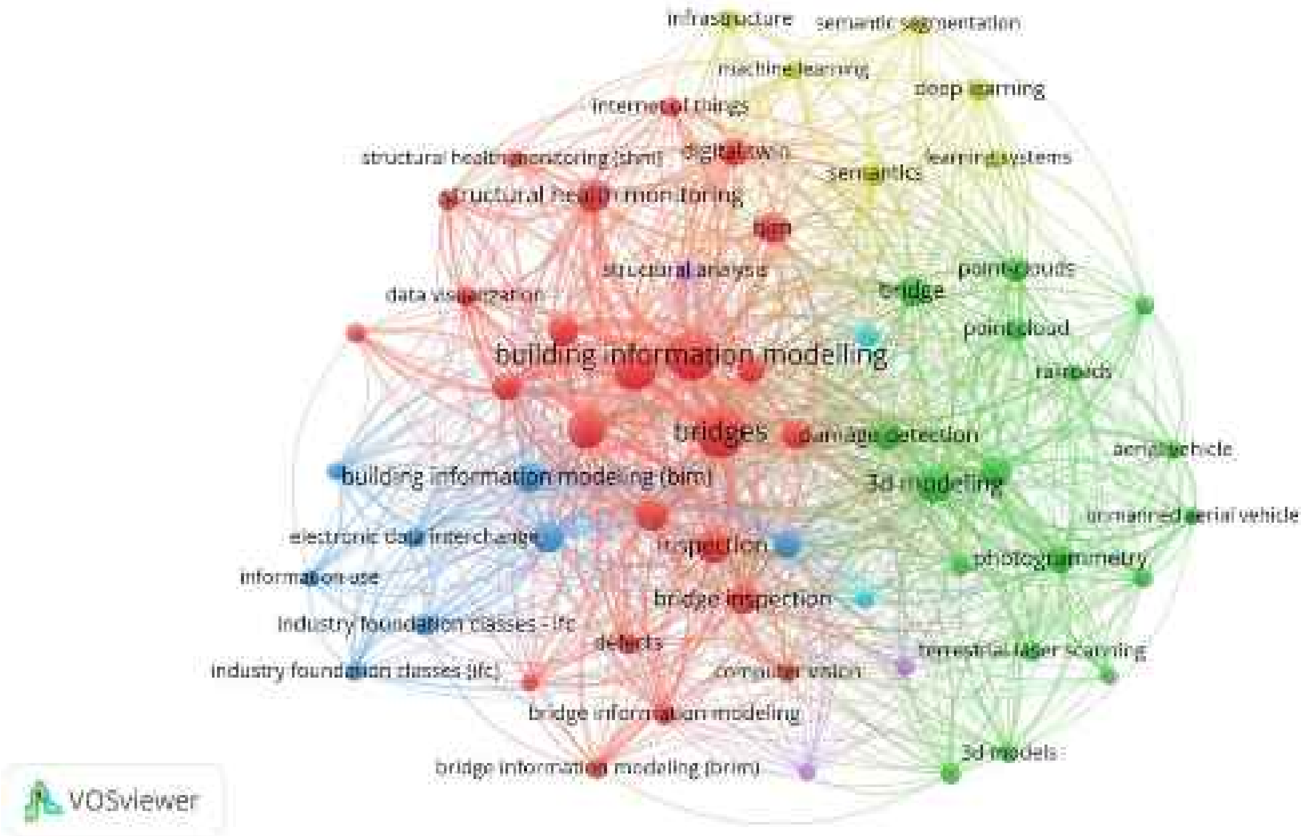

Fig. 8 Keywords co-occurrence

the 50 most frequently used keywords. Similar to the analysis reported in the previous subsection concerning Fig. 4, the terms "bim", "building information modeling", "building information modeling (bim)", "bridge inspection", and "digital twin" are the most frequently used. The word cloud also shows notable visibility for other terms such as "bridge information modeling (brim)", "structural health monitoring", "industry foundation classes (ifc)", and "damage detection". It reflects that the selected literature focuses on aspects of BIM, DTs and bridges in contexts involving damage detection, inspections, and SHM, including substantial utilisation of point cloud technology.

The keyword co-occurrence map generated through the VOSviewer tool (version 1.6.20) shows the interconnections between various terms. Among the terms, strong links between keywords like "building information modelling", "bridges", "3d modeling", "structural health monitoring", and "digital twin" are observed. In addition, larger circles show a high frequency of these terms, as previously mentioned.

4 Content Analysis

4.1 From BIM to BrIM

4.1.1 BrIM Paradigm

The acronym BrIM refers to BIM when applied to bridges [9, 13, 55, 66, 73–76]. Although the term BrIM has been used for some years, it is not included in the official terminologies of bSI. Due to trademark issues, attempts were made to replace the term with "BIM for Bridges and Structures" [13]. The body of research suggests that Stuart S. Chen and Arun M. Shirolé's study, in 2006 established the concept of "Bridge Information Modelling" for the first time [13, 17, 62]. This study aimed to accelerate the design and delivery of bridges, and the concept was partially implemented in TransXML [13, 17, 62]. TransXML is a collection of transportation data exchange protocols using XML (Extensible Markup Language) [66]. A pilot study aimed at creating and evaluating a 3D-centric model for an integrated design and construction process for highway bridges was released in the same year by the NCHRP—USA [13]. In the early 2010s, the Federal Highway Administration (FHWA) in the USA undertook extensive studies to investigate and promote methods for improving the quality and durability of bridges and roadway constructions [13]. OpenBrIM, an open and free cloud-based platform written in XML [13, 55, 62, 77], was created due to these investigations, which concluded around 2015 [13, 62]. However, when OpenBrIM was created, it did not support interoperability between different software systems, as it was based on a single data repository to extract modelling components rather than effective data interoperability [13, 62].

Initially, both OpenBrIM and BrIM approaches were independent initiatives with no formal link to BIM. However, after the launch of OpenBrIM, efforts were undertaken to align the approaches with existing BIM schemas and standards [13]. These efforts included producing documentation on required exchanges between software across the bridge lifecycle, given implementation following the bSI and related ISO standards [13]. Meanwhile, other BrIM studies conducted by different scholars were underway, including IFC schema extensions to IFC-Bridge, to improve and enable the exchange of parametric bridge models [78, 79]. One of the early results from bSI included the presentation of IFC-Bridge in 2019 as a part of IFC 4.2 [80], which was later withdrawn [18] to harmonise and unify all infrastructure domains into IFC 4.3 [8]. Currently, IFC 4.3 is in use, and discussions about IFC 5 have begun [55]. This version may be preceded by IFC 4.4, currently under development [18], and aims to update and enhance the current version, mainly to include tunnel functionalities [8, 18]. Bridges were given priority over other horizontal infrastructures as they are close to buildings [29]. However, there were delays in incorporating them and other linear infrastructures into bSI because there are significant differences in how horizontal infrastructures are geometrically and semantically modelled compared to buildings [30, 37, 78]. Akanbi and Zhang [78] point out three significant discrepancies: (i) the structure of components in linear infrastructures differs from those of buildings (e.g., openings such as windows or doors in buildings do not exist in linear infrastructures); (ii) the terminology used for linear infrastructures can differ from that for buildings (e.g., in bridges, the term "pier" is generally used, whereas for buildings, it is "column"; "girder" and "stringer" are terms used in bridges, while in buildings, these elements are always called "beams"); and (iii) the modelling procedures and techniques for buildings differ from those for linear infrastructures (buildings are more vertical, while linear infrastructures are more horizontal. Kwon et al. [30] further observe that "piers" (for bridges) and "columns" may have similar geometry, but respond differently to dynamic loads, which is critical for structural analysis. Costin et al. [66] highlight the difference regarding the Level of Development (LoD). In buildings, the LoD generally concentrates on interior specifications, whereas for bridges, the priority is on exterior specifications, encompassing geometric details and respective semantic data.

With the recent ISO approval and accreditation of the IFC 4.3 schema, appropriate specification within the IFC schema defines the type of infrastructure and its components, all within the BIM framework. However, besides BrIM, other complementary non-official terms are sometimes used. For example, "bridge BIM" as BrIM synonymous [8], "Transportation Information Modelling (TIM)" [81] and "Infrastructure BIM (IBM)" [47] are used to refer to broader transportation infrastructures, and "Civil Information Modelling (CIM)" for all civil structures [66, 80, 81].

In studies involving BIM for bridges, it is common for researchers not to explicitly use the term BrIM or any of the other terms above (see, for instance, [31, 34, 36, 66, 80, 81]). As for the BIM, Adibfar and Costin [21], Hosamo and Hosamo [22], and Xia et al. [75] state that BrIM is not merely a 3D representation of a bridge but a full model that includes all components of the bridge infrastructure throughout its lifecycle.

This discussion, complemented by the following Sect. 4.1.2, answers the RQ1.

4.1.2 Current Trends in BrIM Usage

Even though BrIM was not part of the bSI framework, the rising digitalisation of infrastructure in recent years has prompted its investigation and exploration, particularly with the rise of BIM [74, 82, 83]. Besides the OpenBrIM approach, various studies and projects have explored the BrIM concept by adopting and adapting existing BIM schemes to satisfy the specific needs of horizontal infrastructures, particularly to support the life cycle processes of bridges [21, 32, 78]. For instance, a few years ago, the American Association of State Highway and Transportation Officials (AASHTO) in the USA adopted the IFC as the standard scheme for electronic engineering data exchange [13]. Jiménez Rios, Plevris and Nogal [55] highlight the advancement of the OpenBrIM platform since its early stages. The platform has been one of the resources available for developing, studying, and managing bridge projects [62, 77]. The platform sponsored by FHWA [62], despite not being part of the bSI, currently incorporates IFC into the variety of its interoperability platforms [77]. In addition to parametric 3D modelling, OpenBrIM incorporates other functionalities, such as finite element (FE) modelling, SHM, and construction management tools [77]. These aspects show progress towards taking BrIM to other levels, such as the BDT for SPMM [21, 22].

BrIM has been employed across various lifecycle phases [6, 21, 32, 78, 84], and can be combined with other technologies, systems, or processes to maximise its benefits. In the design and construction phase, the literature suggests that the focus is analogous to the traditional BIM (for buildings), including collaborative design, multidimensional (nD) modelling, visualisation, clash detection, cost estimation and data management [6, 9, 37, 76, 84]. BrIM-based models enable precise material estimation during the planning and construction phases, influencing the bridge lifecycle. For instance, it is within this context that Girardet and Boton [37] developed a parametric modelling methodology within BIM, aiming to provide greater flexibility for preliminary bridge design and potential future adjustments. As they note, since alterations in projects are frequent and updates must be made quickly, a significant amount of time is often wasted during the development of initial projects and their subsequent upgrade. Kim et al. [79] developed a prototype based on a 3D intelligent object model to reduce the time and effort necessary for bridge management design and construction. The developed prototype allowed for the automation of overall design and construction calculations, such as estimating cost and schedule based on a 3D model. Gragnaniello et al. [35] adopted a BIM-based approach to create a digital ecosystem to optimise information management throughout the entire design process of a concrete viaduct. The authors compared traditional design methods with the digital methodology they proposed. Simulated sensors were included in the digital environment to aid in structural simulations. The comparison between traditional design approaches and the digital approach centred on the following aspects: (i) project monitoring plans—2D CAD vs. 3D digital models with simulated sensors; (ii) document exchange—manual/email/database vs. Common Data Environment (CDE); (iii) design tools—undefined/manual vs. BIM-FE modelling; file exchange—closed formats vs. open standards; (iv) check of specifications—paper vs. BIM-based check; and (v) system supervision—manual vs. automatic. So, significant advantages were observed in the digital ecosystem approach over traditional methods.

BrIM has been employed in its basic form in operation and maintenance [76] or attempting to combine with other technologies, systems or processes, such as when developing a BDT [6, 20, 21, 23]. The technologies, systems and processes involved include FE modelling, SHM [6, 9, 20, 21, 23, 27, 35, 85], IoT, wireless communication, edge-cloud computing [6, 20, 23, 27], VR/AR/MR [6, 20, 23, 81], and AI/ML [6, 20, 22, 23, 27, 31, 74]. This approach is often motivated by the need of integrating and visualising relevant data regarding the bridge condition, such as damage [6, 23, 27, 29, 33, 34, 36, 74, 84, 85], typically in real-time [23, 27, 74, 81, 84, 85]. By updating both geometric and non-geometric data (e.g., damage evolution), this approach shifts BrIM models from static to dynamic representations [6, 27, 85, 86], ensuring an accurate depiction of the bridge asset as conditions change over time [23, 74]. For example, to enhance assessment and decision-making on bridge conditions, Adibfar and Costin [21] developed a DT of a mock-up bridge by using real-time weigh-in-motion (WIM) data. On-site sensors for real-time data collecting were employed, together with Revit software for data representation. Bouzas et al. [87], used the basis of BIM for structural health control of historical steel bridges by implementing a four-step model: (i) 3D reconstruction created in Revit and based on historical data and laser scanners (the architectural model); (ii) Allocation of the architectural model in cloud with URL links that allows updates from different stakeholders; (iii) structural model generation in Ansys software (from architectural model); and (iv) continuous updates of architectural and structural models based on new data, and comparing with previous conditions for performance evaluation. The authors reported interoperability issues, particularly in structural model generation from architectural models in IFC format, likely due to a lack of established interoperability between Ansys and BIM software. So, because of this, the authors used the .dxf file format to generate a structural model. Regarding the BIM/BrIM approach and interoperability, the architectural model was created using building-type approaches, with profiles considered as combinations of plates and L-profiles. The authors did not address treating other specific elements, such as supports, bearings, or damage modelling.

Hamdan et al. [31] proposed using BIM approaches and Semantic Web Technologies (SWTs) to automate structural damage evaluation in bridges. The method proposed by the authors included using high-resolution images and georeferenced point clouds, which are then represented in a 3D BIM bridge model (the BrIM model). A web ontology semantically identifies and evaluates anomalies by employing predefined rules, providing results for subsequent structural analysis and simulations. Through a test case involving a concrete beam with induced damage, the authors validated the approach to show the method's benefits in improving bridge maintenance and inspection. While the integration of BIM and SWT for automated damage evaluation in bridges appeared innovative, the authors did not address issues related to the flexibility of the method, particularly considering the time-consuming nature of processing large datasets and generating semantic web ontologies. Honghong et al. [6] conducted a literature review on DT-enhanced BIM for bridges, where they assessed the integration of emerging technologies within an ecosystem comprising data gathering, transfer, and sharing, 3D design, visualisation, and simulations. The authors highlighted several obstacles to the application of BDTs, including limited monitoring data for several ageing bridges, challenges in achieving real-time performance, and the absence of a unified open-source platform. Despite the challenges, the authors emphasised the significant potential for integrating these emerging technologies with BIM approaches for bridges to drive digital innovation in the bridge industry, thereby potentially enhancing the efficiency and sustainability of bridge infrastructure. Jasiński et al. [20] used a BIM-based FE model to develop a BDT for bridge load testing control. The BIM model of the bridge was developed using existing 2D drawings and Revit software, and the FE model was subsequently generated using a custom plugin. The BDT was then used to evaluate the loads and responses of the structure and compare the results with computational FE model-based simulations.

BrIM has also been integrated into Bridge Management Systems (BMS) [9, 29, 33, 74, 84], either as a BDT or in its basic form. BMS is an integrated system for managing bridges, allowing for data storage, processing, and management, as well as supporting engineering workflows, asset management, and strategic resource planning [9, 23, 29, 33]. Bridge inspections and SHM are among the primary functions of a BMS [22, 23]. For example, Jeon et al. [84] focused on existing bridges that were initially built without BrIMs and developed a four-part framework aimed at bridge inventory and integration of inspection data to improve efficiency in maintenance. The framework included: (i) planning (e.g., qualitative survey and information requirements); (ii) Design (e.g., system architecture, data integration); (iii) Development (e.g., inventory system, data-driven model, model library and templates, image mapping and AI-based damage detection); and iv) implementation (e.g., BrIM application, target bridge selection, and inspection data survey). Although the authors did not include any IFC extensions for 3D BrIM modelling, they handled the issue by employing predefined data templates and modelling libraries. By exploring the digital twinning concept, Mohammadi et al. [74] developed a BrIM-oriented plugin to improve BMS. The plugin consisted of three layers: (i) a 3D CAD model developed with Terrestrial Laser Scanning (TLS) point clouds and loaded into Tekla software for IFC-format 3D modelling; (ii) a cloud-based user interface application built with Microsoft Visual Studio and Tekla's open API (application programming interface) to implement a Decision Support System (DSS); and iii) report generation. Given the difficulties associated with real-time monitoring and updating, it is unclear whether TLS data is used only for initial CAD model generation or continual non-geometrical data updates.

In summary, based on this discussion and the approach outlined in Sect. 4.1.1, RQ1 can be fully addressed by acknowledging that BrIM has progressed considerably from its BIM roots. Key advancements, such as the introduction of bridge-specific components in IFC 4.3 and the emergence of OpenBrIM as a cloud-based solution, have enabled BrIM to support the whole bridge lifecycle, similar to BIM for buildings. Efforts are underway to integrate emerging technologies and different systems, such as IoT, AI/ML, and SHM, with the goal of improving real-time monitoring, predictive maintenance, and decision-making. However, issues such as interoperability and scalability persist, and overcoming them is crucial for fully realising BrIM's potential in modern bridge infrastructure management.

4.2 BrIM Models of Existing Bridge Assets: Digitisation Strategies

4.2.1 Overview

Numerous studies have emphasised the benefits of BrIM, as a transformative technology in the bridge infrastructure sector [22, 74]. In the case of existing bridges, supporting SPMM has been a major focus [22, 84, 88]. As noted by Hosamo and Hosamo [22], while some recently constructed bridges may incorporate BrIM from the design stage, most existing bridges rely on traditional information management methods, such as datasheets. It reveals the vital importance of producing as-is BrIM models to foster the digitalisation of the life cycle management of existing bridges.

The bridge geometry must be generated using a specific digitisation strategy to develop an accurate as-is BrIM model [87]. The initial outcome of digitising an existing bridge is often an as-is 3D digital model (3D digital reconstruction), which may also include corresponding 2D representations. Different approaches to 3D digital reconstruction have been reported in the literature, with some being more widely applied than others. However, few studies have been conducted to synthesise the various approaches and their advantages and challenges. Addressing this gap is among the objectives of this paper.

Four models are worth highlighting in the process involving developing the as-is BrIM model: (i) as-is 3D digital model; (ii) semantically enriched as-is 3D model; (iii) as-is BrIM model; and (iv) semantically enriched as-is BrIM model. Although the first one is sometimes misidentified as the true as-is BrIM model, it is merely a geometric representation of the bridge geometry/geometry capture. The model may be in the form of simple 3D CAD or 3D point cloud reconstruction, when the 3D CAD is derived from point cloud data (PCD) [22]. In the semantically enriched as-is 3D model, the semantic data about the bridge components are added to the 3D digital model. However, the interoperability of the model within the BrIM framework is not guaranteed. To be interoperable, it must comply with the exchange data schemes, such as the IFC structure or relevant IFC extensions. In such a case, the model may be considered an as-is BrIM. For the semantically enriched as-is BrIM model, the BrIM model is generally enriched with data related to structural performance (e.g., damage information). To fully integrate this information and ensure interoperability, it generally requires extending or adapting existing IFC entities [30, 89], using property sets [1, 4, 5, 17, 30, 33–36, 68, 89, 90], or applying relevant ontologies [1, 6, 30–32, 36, 69, 80, 91]. Measurements are taken from existing drawings and archival documents (typically 2D), and physical inventories are gathered on-site to achieve accurate geometrical characterisation of existing bridge assets [20, 78, 87].

The digitisation process involves several techniques, including the "point cloud", which is obtained using laser scanning and photogrammetry (or other imaging procedures) [8, 17, 20, 22, 31, 66, 87, 88, 92], as well as parametric and data-driven approaches [6, 32, 37, 38, 84, 88], being common to combine some of the methods [33, 87]. As presented in Table 7, the strategies for generating as-is BrIM models (or simple 3D model as antecedent step of BrIM model) are divided into three groups: Group 1—Point cloud-based approach (employing laser scanning and photogrammetry or videogrammetry); Group 2—Parametric and data-driven modelling approaches; and Group 3—Hybrid approaches and other methods (involving a combination of different approaches, direct modelling using BIM/BrIM authoring tools, and other less commonly applied techniques).

The current trend in developing as-is BrIM models emphasises the use of more dynamic approaches to automate or semi-automate processes. It reduces the need for manual intervention, saves time, and enhances precision and design efficiency, making methods from Groups 1 and 2 very attractive, as well as the combinations that include these methods in Group 3 [6, 32, 37, 38, 66, 88, 93]. Other dynamic solutions are less popular and less widely used. For instance, "generative modelling" in Group 3 offers a novel technique by automatically creating new 3D models by combining principles from computer graphics, ML, and geometry processing [78].

Table 7 shows that the strategies in Group I (point clouds) and Group III (hybrid and other methods) dominate in developing as-is 3D/BrIM models. Since point clouds are also included in hybrid approaches, it becomes evident that the point cloud approach, whether used solely or in conjunction with other techniques, stands out in generating these models. This is consistent with the results provided in Table 5, where most studies are associated with reality capture/scan-to-BIM techniques. Nonetheless, other approaches, such as parametric and data-driven modelling (group II) and direct modelling (included in group III), are also widely used. Additionally, most studies in Group I that simply used the point cloud approach produced very few BrIM models, instead, they focused on simple as-is 3D models. Looking at each group, Group I has more studies exploring photogrammetry than laser scanning, probably due to the higher costs associated with the latter. However, all studies in this group that explore photogrammetry only show the generation of simple as-is 3D bridge models, not BrIM models. In Group II, concerning parametric and data-driven modelling, most studies demonstrate the generation of as-is BrIM models. Most studies in Group III use direct modelling (from BIM/BrIM authoring) to build as-is 3D/BrIM models, followed by hybrid approaches that combine point clouds and direct modelling. Most studies in this group also demonstrate the development of as-is BrIM models. It is worth mentioning that not all the BrIM models developed in these studies show a high LoD. A brief description of as-is 3D/BrIM model generation strategies for each group, including their advantages and limitations, is provided next.

The overview presented here, along with the forthcoming description of these strategies, and the later discussion on

Table 7 Strategies for generating as-is 3D bridge and BrIM models

Group	Strategy approach		References			
			Modelling achievement		Mention of strategies	
			3D model	3D BrIM model	Subtotal	Total
I	Point cloud	Laser scanning	[2, 75, 92, 94],	[74, 95]	6	23
		Photogrammetry	[41, 59, 63, 65, 92, 96–102]		12	
		Videogrammetry	[103]		1	
		Laser scanning + photogrammetry	[82, 104, 105]	[58]	4	
II	Parametric and data-driven		[38, 40],	[3, 84, 91, 106–111],	11	12
III	Hybrid and other methods	Direct modelling (from BIM/BrIM authoring)	[34]	[20, 21, 61, 85, 90, 112, 112–118],	14	23
		Point cloud + direct modelling		[71, 76, 119–121],	5	
		Point cloud + parametric modelling		[70, 122]	2	
		Generative modelling		[78, 123]	2	

BrIM interoperability in Sect. 4.3, provides a comprehensive answer to RQ2.

4.2.2 As-is BrIM Model Generation Based on Point Cloud

Currently, generating as-is BrIM models is one of the primary goals when performing 3D reconstruction of bridges using point clouds [22, 33, 36, 40, 63, 73, 81, 88, 103, 122, 124]. It is worth noting that 3D reconstruction, typically in the form of a 3D mesh or 3D CAD, also serves as the basis for various purposes, such as inspections and structural analysis [58, 60, 71, 87, 88, 112], and simple digital documentation of historical bridges [41, 58, 71, 125] (sometimes not related to BrIM).

A point cloud is a collection of data points in 3D space, each specified by location (x_i, y_i, z_i) and additional attributes such as colour and intensity [92, 101, 112, 122, 126, 127]. Laser scanning (using 3D scanning technologies like LiDAR and laser scanners) and photogrammetry (based on image capture) are two common reality capture methods used for generating point clouds [8, 17, 20, 22, 31, 33, 36, 41, 58, 66, 71, 74, 81–83, 88, 89, 112, 122, 125–127]. UAVs, or drones [128], are often equipped with high-resolution cameras and LiDAR systems to facilitate these methods, enhancing data collection efficiency [33, 101]. Advancements in reality capture methods, including ready-to-use point clouds [22] and UAVs incorporating additional software for efficient 3D reconstructions [17], have increased interest in using point clouds for 3D bridge reconstruction owing to the improved precision [22, 126]. Additionally, these methods are particularly useful when project documentation is limited or when there are discrepancies between design and as-built conditions [22, 126].

The 3D bridge reconstruction process through laser scanning or photogrammetry is well-documented in the literature [64, 86, 93, 101]. Both approaches generate a 3D point cloud, which can be transformed into a 3D mesh. The 3D point cloud or mesh can be loaded into CAD software for conversion into a parametric CAD model [86]. These 3D mesh/CAD models are not semantically rich, which means they do not contain detailed information [17, 31, 86, 122]. When the objective is to obtain an as-is BrIM model, the approach now falls within the wider field of "scan-to-BIM" [2, 17, 20, 36, 40, 71, 82, 94, 124, 125], where the core idea is to build BrIM models from PCD, 3D meshes, or as-is 3D CAD models (obtained from PCD).

There has recently been substantial research into developing as-is BrIM models using point clouds [17, 73, 82, 124]. For example, Achuthan et al. [73] showed how point clouds from drone-based bridge surveys can be converted into BrIM models using Revit software. Autodesk ReCap cleans, and merges point clouds into a format compatible with Revit (.rcp). The imported point clouds are then used for geometry tracing and creating IFC elements. The authors applied this procedure to generate an as-is BrIM model, which was then integrated with Geographic Information System (GIS) data for use within BMS. However, considering the BIM software is more suited to buildings, only basic elements were applied to the model, and the terminologies used were also of buildings. Pepe, Costantino and Garofalo [71] used aerial and terrestrial photogrammetry to gather PCD and create a BrIM model of a historical bridge. From the obtained PCD, the authors used Rhinoceros software to filter the PCD and create different profiles with the Grasshopper plug-in, resulting in a 3D mesh. After this process, it was possible to identify elements on the mesh, including vaults, retaining walls, and pylons. The 3D mesh was then imported into the Revit software for various operations (e.g., creating BIM objects) and generating a BrIM model. Hosamo and Hosamo [22] and Xia et al. [75] described three processes that follow 3D reconstruction using reality capture methods: (i) semantic modelling, in which subsets of the 3D model are labelled according to a BIM taxonomy; (ii) Geometric modelling, which involves creating a parametric representation that defines the shape, position, and spatial relationships of each class instance; and (iii) BrIM formation, which combines semantic and geometric modelling. Lee et al. [124] describe a process similar to that of Hosamo and Hosamo [22] and Xia et al. [75], and emphasise the necessity of semantic segmentation to assign information to the PCD and parameter extraction to obtain numerical data such as height, length, and width. These processes may rely on advanced AI/ML methods [40, 63, 75, 82, 124] or sophisticated algorithms [95, 122]. Lee et al. [124] used this basis to create an as-is BrIM model and implemented specific improvements to handle complex bridge components by adopting a three-step approach: (i) noise reduction over the PCD, (ii) 3D transformation (of bridge PCD) for axis orientation, and (iii) design parameter extraction and linkage to a parametric BIM library. Martens et al. [82] and Mansour et al. [2] explored similar methods for developing as-is BrIM models and pointed out four key stages: data acquisition and pre-processing, semantic segmentation, 3D modelling, and BrIM model generation. Martens, Blut and Blankenbach [82] used this approach to explore ML techniques for semantic point cloud segmentation applied to bridge structures. Lee et al. [40] developed a BrIM modelling algorithm based on bridge components derived from point cloud segmentation and classification. The classification process was based on statistical methods and a database containing information on various types of existing bridges. The BrIM modelling algorithm was created with Dynamo, a visual programming tool included in the Revit platform.

Scan-to-BIM approaches provide substantial benefits, particularly in automating as-is 3D bridge model generation and semantic enrichment [33, 40, 122]. These methods rely on reality capture technologies offering flexible and cost-effective geometrical modelling solutions [33, 66]. As previously stated, reality capture methods underpin scan-to-BIM and may be useful in producing digital documentation for new bridge parts introduced during the post-construction period [33]. Additionally, scan-to-BIM is regarded as one of the pathways for developing BDTs from scratch [22, 33, 82].

Despite these benefits, several issues persist. While reality capture technologies are increasingly available, when laser scanning is particularly needed the equipment cost can pose an obstacle [66, 127]. On the other hand, creating point clouds through photogrammetry can be time-consuming and labour-intensive [33]. The automatic recognition and accurate modelling of bridge components from point clouds are still complex tasks [17, 22, 122], which makes it challenging to create BrIM models that are detailed and semantically rich [17, 122]. Therefore, manual intervention is still frequently necessary in point cloud-based as-is BrIM generation [112]. Most studies developing as-is BrIM from reality capture methods have tended to model bridges similarly to buildings, or utilising building-specific tools, resulting in BrIM models with low LoD and limited interoperability [122]. Some researchers have focused more on 3D bridge reconstruction, PCD segmentation, and parameter extraction [124], than on semantic enrichment and interoperability, both crucial for effective BrIM model generation. This indicates a more significant need for post-3D point cloud generation advancements for more comprehensive as-is BrIM model generation.

As part of the answer to RQ2, it is worth mentioning that point cloud-based approaches have been proving to be quite effective in digitising bridges. UAV-assisted techniques, laser scanning, and photogrammetry have transformed data collection, allowing for quick and accurate 3D bridge reconstruction. Nevertheless, these methods frequently fail to produce comprehensive and semantically rich BrIM models, especially when photogrammetry is applied alone. A significant challenge lies in automating the recognition of bridge components, which still require extensive manual involvement. Despite these limitations, point cloud techniques remain an important step towards bridge digitisation. They are increasingly being combined with other approaches, including parametric modelling, to enable more automated BrIM solutions.

4.2.3 As-is BrIM Model Generation Through Parametric and Data-Driven Approaches

The implementation of BrIM has been facing significant hurdles related to geometric and semantic variations amongst bridge structures [37, 38]. Given the complexity of bridge structures and the growing amount of data throughout their life cycle [38, 109], classical direct modelling approaches are becoming less effective in the current context [40, 84, 109] despite their ongoing widespread usage in the industry [38]. Recent studies highlight parametric and data-driven modelling approaches as potential solutions to these issues, offering increased efficiency in developing BrIM models while saving time [6, 37, 38, 84, 109]. These methods allow designers and other stakeholders to alter BrIM model inputs to match specific requirements dynamically, increasing flexibility in model development and application [38, 109].

Parametric modelling, in particular, focuses on using parameters and algorithms to generate shapes or models by varying input values, allowing users to explore numerous design solutions and automate complex changes directly through code [6, 37, 109]. Unlike classical direct modelling, which restricts users to predefined shapes and simple actions, parametric modelling gives users practically complete access to model data [37, 109]. OpenBrIM is a notable example of parametric modelling since it allows users to customise and develop BrIM models to fit their own needs [77, 109].

The data-driven modelling approach, on the other hand, operates at a macro level and commonly incorporates parametric modelling, which may be considered a micro-level approach [109] (Fig. 9a). The data-driven modelling approach leverages data to guide the BrIM modelling process and can be separated into three components: (i) the database, (ii) BrIM protocols, and (iii) the BrIM model [109]. The database may contain, among others, predefined component data related to various bridge types, which are typically based on a Bridge Inventory System and can be combined to generate BrIM models for specific bridge types [84, 109]. BrIM protocols are applications that employ algorithms and APIs to assemble components geometrically and/or integrate non-geometric data. Examples of BrIM protocols include Grasshopper (included in Rhinoceros software), Dynamo (included in Revit software), OpenBridge Modeller from Bentley, and open-source-based design scripts [37, 109]. Parametric modelling may be integrated both into the database (allowing for dynamic modifications of components), and within protocols.

As depicted in Fig. 9b, parametric modelling for partial or full BrIM model generation may typically involve four parts: (i) input data (geometry and semantic data); (ii) a basis of parameters; (iii) processing (algorithms for geometric operations and non-geometric data integration); and (iv) outputs (e.g., BrIM objects or the final BrIM model) [37]. Input data formats include lists, curves, surfaces/2D drawings, and pre-existing objects [6, 37, 108, 109]. Shim et al. [108] highlight that this approach can generate parametric files for specific BrIM models. For instance, the authors explored the strategy to create a single parametric file capable of creating BrIM models for multiple bridge types.

Several case studies have been introduced through exploring parametric and data-driven approaches as follows: Dang

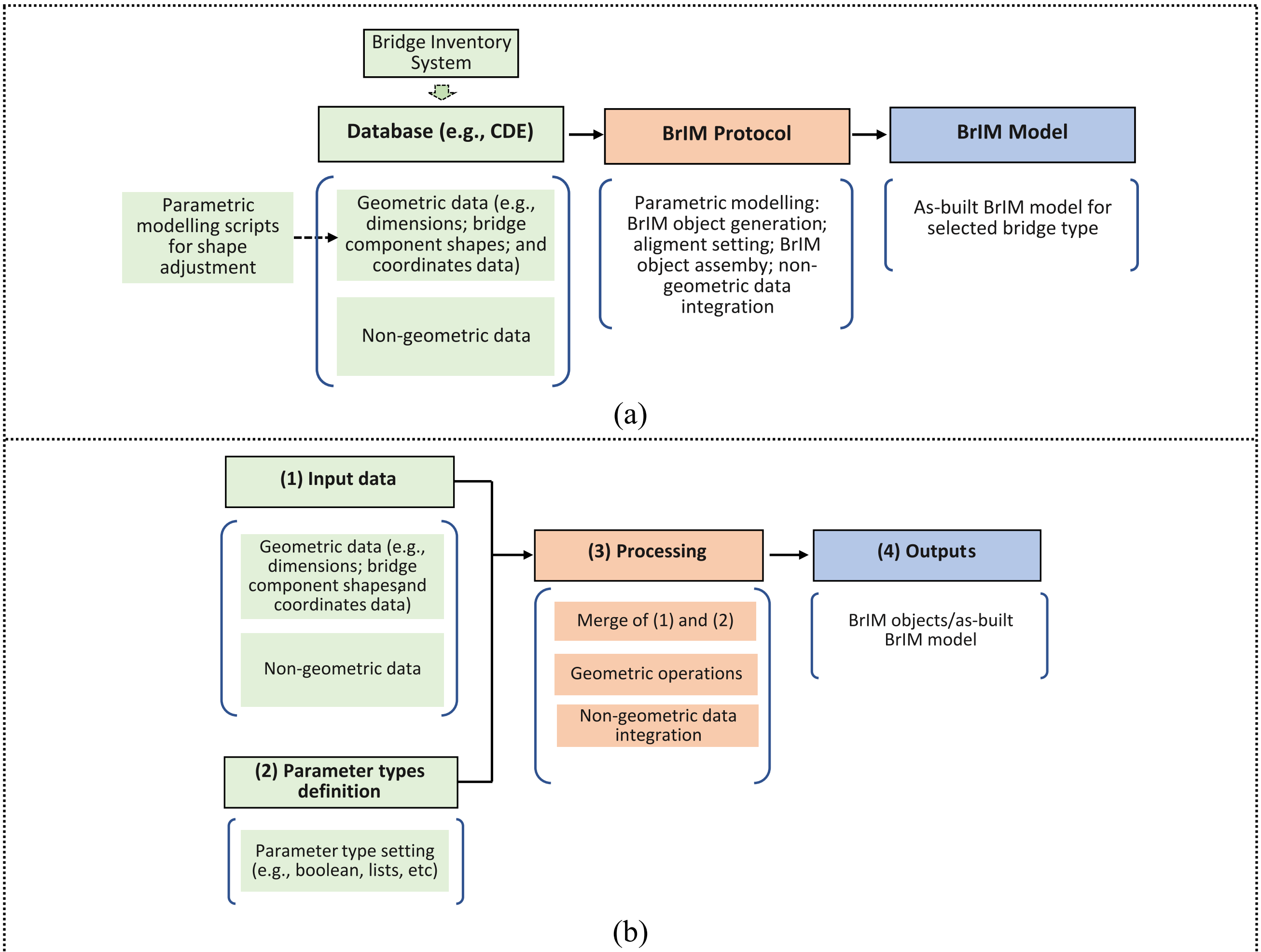

Fig. 9 Parametric and data-driven approaches: **a** Data-driven; **b** isolated parametric modelling

et al. [109] employed parametric and data-driven modelling approaches to create a BIM-based master digital model for suspension bridges. Shim et al. [108] developed a BIM-based BMS for cable-stayed bridges, which relied on parametric 3D modelling to enhance design and foster better data management and interoperability during inspection and maintenance activities. Similarly, Sousa et al. [38] developed an automated method for creating box girder bridge models, where geometric parameters were defined to adhere to current design standards. Jeon et al. [84] proposed a BrIM-based BMS for existing bridges, which allows users to complete BrIM models quickly using pre-defined Excel data templates.

Parametric and data-driven modelling approaches provide substantial benefits in bridge engineering, notably in automating the design process and allowing for dynamic modifications [38, 40, 84, 108, 109]. These approaches enable seamless updates, reduce manual interventions, and can easily be integrated into BMS [84]. Input information can be preserved, updated, and archived throughout the project's lifecycle, ensuring that important stakeholders can access the data at any time [108]. The parametric 3D bridge model aligns with several processes or technologies, including FE modelling and BDT [6, 38].

Along with the significant benefits that parametric and data-driven modelling approaches offer, notable drawbacks and challenges must be considered. The procedures can become complex and error-prone due to the large number of input data and parameters required, especially for large-scale and complex bridges [37]. The algorithms normally rely on complex mathematical formulas for geometry and orientation definition [108]. Managing numerous input data and parameters can be challenging and demand robust algorithms. To address this, Sousa et al. [38] have suggested employing automated methods that require fewer input data and parameters, allowing for the production of a prototype model that can be enhanced with user feedback. Additionally, many existing bridges lack BrIM data, and much of the existing design information is only available in hardcopy, making digital conversion a time-consuming and expensive operation [63, 84].

Contributing to the answer to RQ2, parametric and data-driven approaches are distinguished by their potential to generate detailed BrIM models when compared to point cloud-based strategies. They offer flexibility by dynamically adjusting digital models, yet they require a huge amount of input data and complex algorithms, which can lead to inaccuracies, especially in large-scale projects. Challenges include the lack of BrIM data for existing bridges and the labor-intensive digitisation of hardcopy drawings. Despite these challenges, these strategies show great potential for automating bridge digitisation, data integration, and enabling seamless updates, being a key focus for future research.

4.2.4 Hybrid Approaches and Other Methods for as-is BrIM Model Generation

Apart from classical direct modelling, as previously stated, point cloud-based modelling, parametric and data-driven modelling are prevalent methods for developing as-is BrIM models. Other initiatives researched alternative approaches, such as generative modelling [78, 123]. As referred by Akanbi and Zhang [78] generative modelling automatically creates new 3D models by combining computer graphics, ML, and geometry processing techniques. For example, using this technique, the authors developed a framework to semi-automatically convert 2D orthographic bridge drawings into 3D information models and IFC files.

Hybrid approaches are also other commonly used strategies in generating as-is BrIM modelling. They combine different modelling techniques and can increase accuracy and efficiency and achieve more comprehensive models by leveraging the capabilities of each technique. Numerous studies have shown the benefits of beginning with PCD generation, sometimes involving segmentation and parameter extraction, before moving on to direct or parametric modelling. For instance, Yang, Cheng and Wang [70] developed a semi-automated solution to reduce manual work and the large amount of time necessary for post-processing point clouds to generate as-is BrIM models applied to steel bridges. They combined laser scanning and parametric modelling, employing algorithms to automatically extract geometric information from the generated PCD and automatically create a parametric BrIM model. Qin et al. [122] applied a similar strategy for a concrete bridge, employing a four-step process: (i) bridge point cloud generation; (ii) point cloud segmentation; (iii) parameter extraction; and (iv) API-based parametric modelling to link extracted parameters with BIM authoring software. Revit and Dynamo were utilised as BIM authoring and the API, respectively. Owing to insufficient information from extant designs, McKenna et al. [76] used laser scanning to create a 3D point cloud of a steel bridge, which was subsequently imported into Revit via ReCap for manual modelling and final BrIM generation. Vital et al. [119] employed multiple software tools to generate an as-is BrIM model of a concrete bridge. Trimble RealWorks was used for point cloud segmentation and feature extraction, SketchUp for initial model development and IFC compilation, and Revit for refinement, which included creating a set of object families and respective customisation.

These as-is BrIM digitisation strategies, classified under Group III in Table 7, complement those previously outlined, namely cloud-based approaches (Group I) and parametric and data-driven approaches (Group II), collectively contributing to the partial answer to RQ2. These approaches represent the principal methodologies currently employed for generating as-is BrIM models.

The multiple strategies for as-is BrIM model creation, demonstrate the importance of selecting solutions based on specific requirements, such as bridge structure complexity, data availability, and desired level of detail.

4.3 Interoperability and Semantic Enrichment in BrIM

Interoperability is currently seen as a critical aspect in managing the built environment to avoid data loss and the high costs and delays associated with employing paper documents or fragmented information in different formats [8, 34, 36]. While there are still challenges to full interoperability, BIM has advanced dramatically in this area, particularly with successive IFC updates, which have proven effective in various applications [30, 36]. This success in buildings has driven efforts to include other infrastructures, such as bridges [8, 36, 62], which are now integrated into the latest version of IFC, IFC 4.3 [7].

The existing body of literature indicates that interoperability in BrIM is primarily achieved through the use of IFC standards [8, 13, 21, 30, 55, 62, 66, 79]. OpenBrIM emerged as an alternative [13, 30, 55, 62], whereas TransXML and LandXML, created for transportation data exchange, did not achieve widespread industry adoption [66]. As stated by Costin et al. [66], IFC includes three data formats: (i) one based on the STEP physical file structure; (ii) another using XML document structure; and (iii) a third in a compressed format. OpenBrIM platform currently includes interoperability with BIM models for software such as Autodesk, Bentley, and Trimble Solutions, with data exchanges in IFC 4.2 format [77]. However, bSI has withdrawn this version [18], and an update to IFC 4.3 is expected for the platform. Additional interoperability provided by the platform includes 2D drawings for programs like AutoCAD and MicroStation, as well as FE Model exchanges compatible with programs like SAP2000, CSiBridge, Larsa 4D, and Midas [77].

Both IFC and OpenBrIM have made progress [15, 55, 62], but some challenges and limitations regarding the full capability of modelling bridges and data exchange throughout the entire lifecycle remain [31, 32, 35, 62, 80]. For instance, regarding the IFC, the latest IFC version does not include all parts of a bridge. ABUTMENT, DECK, DECK_SEGMENT, FOUNDATION, PIER, PIER_SEGMENT, PYLON, SUBSTRUCTURE, SUPERSTRUCTURE, and SURFACESTRUCTURE are the currently included parts [18].

Concerning OpenBrIM, while the related cloud platform includes other functionalities, such as those previously mentioned, it focuses primarily on the 3D representation of bridge structures and lacks maturity in representing bridge monitoring information [52]. The bridge structure is defined as a hierarchy of objects and their parameters, with each object representing a physical entity (e.g., beam, column, deck) or a conceptual entity (e.g., project, group, unit system) [52]. Each parameter represents either an object property (for example, length, width, or thickness) or refers to another object [52].

In the context of bridge engineering, the main challenges associated with using both IFC and OpenBrIM arise during the operational phase, where it is necessary to incorporate information related to structural performance monitoring (e.g., sensor data and anomalies) [30, 31, 34, 36, 126]. To effectively use the BrIM approach for SPMM, it is essential to employ open-standard data models that thoroughly describe bridge structures and monitoring systems to represent and manage the required data [34, 36]. Incorporating and representing information such as damage and structural performance data in BrIM is commonly called the semantic enrichment of BrIM, where relevant information is incorporated into the model [32–34, 36, 47]. Semantic enrichment is essential for bridge asset management operations and is precious when developing a BDT [32, 33]. For example, semantic damage information may include damage type, severity, and extent [33].

Research has been conducted on interoperability and semantic enrichment to enhance BrIM or address existing challenges. Since IFC 4.3 was released only recently, most of the existing efforts have employed previous versions of IFC. IFC entities extension/addition, property sets, ontologies, and data dictionaries, among others, are some of the aspects explored. For example, Kwon et al. [30] developed a framework for bridge SHM using an IFC-BIM-based approach to identify anomalies, highlighting two approaches for representing and managing information for non-building facilities: by adding property sets to the IFC or employing extensions based on the IFC's object-oriented capabilities. Based on the second approach, they used IFC 4.1 (now withdrawn [18]) and employed existing IfcSensor entities to express accelerometer and strain gauge data required for bridge SHM. Park et al. [89] used the IFC extension concept to introduce IFC entities for bridge structures and mesh-free analysis to improve information sharing and interoperability across architectural and structural analysis models. Unlike previously mentioned Kwon et al. [30], who employed an existing entity (IfcSensor), Park et al. [89] added new entities to describe bridge structures. They divided these entities into spatial and physical aspects based on IFC architecture. The spatial entity consisted of IfcBridge (for the bridge itself) and two other entities related to the directions: IfcBridgeSpan and IfcBridgeSpacePart. The physical entities were added to represent physical elements that made up a bridge structure and included IfcBridgeElement (for the components of the bridge), IfcCivilSharedFacility (for elements commonly used in infrastructure facilities), IfcCivilElementPart (for sub-element detailing), and IfcCivilElementAssembly.

Lorvão Antunes et al. [1] argue that, beyond property sets, leveraging ontology models allows for extensive information interchange in BrIM. Ontologies provide a structured framework that defines a set of concepts and categories, including their relationships within a particular domain, in a format readable by humans and machines [32, 91]. For instance, the authors designed and developed an ontology structure to encode shared information from a Data Dictionary related to Asset Management Systems. Currently, bSI provides the buildingSMART Data Dictionary (bSDD), an open-source service that provides a collection of connected data dictionaries that define terminologies for the built environment [18]. The bSDD enables users (organisations) to create and host their own classifications and attributes [18].

Hagedorn et al. [32] and Hamdan et al. [31] consider ontologies and SWTs as emerging trends for enriching BrIM and addressing data exchange challenges. The Semantic Web combines multiple internet resources and enriches them with a semantic layer that contains additional metadata descriptions [31, 32]. On the Semantic Web, data is structured through ontologies created using the Web Ontology Language (OWL) [31, 32]. Hagedorn et al. [32] used the Semantic Web approach to create a web-based platform for visualising, exchanging, and integrating asset management data to inspect and maintain a concrete bridge.

Justo et al. [8] proposed utilising a point cloud approach to automatically generate a truss bridge IFC model and its structural graph. They used IFC 4.1 (already withdrawn, as previously mentioned), but also included preliminary documentation from IFC 4.3 to enhance some functionality, as IFC 4.3 had not yet been released. Individual truss members were modelled using IfcMember, and the overall truss was described using IfcElementAssembly and IfcRelAggregates. Additional entities explored by the authors included IfcLocalPlacement (for defining coordinate systems), IfcLinearPlacement (for linear positioning), IfcExtrudedAreaSolid (for representing each truss member as a solid with a profile and length), and IfcRectangleProfileDef (for the extruded profile and section dimensions).

Hüthwohl et al. [29] investigated using the IFC4 framework to integrate bridge defect data into BIM models. They analysed multiple bridge inspection guidelines and compiled defects into a hierarchical structure, which was then matched with existing BIM standard schema to assess the applicability of the schema in describing the bridge inspection process. They identified categories of defects and required features from guidelines and modelled them as defect entities with properties and relationships. The modelled defect entities included: IfcTask, inherited from IfcProcess (for general information); IfcElementAssembly and IfcPropertySets (for defects and their properties); IfcRelAggregates (to assign the defect to an IFC element) and IfcSurfaceFeature derived from IfcElement (for modelling element defects). Isailović et al. [33] also used the existing IFC4 schema to semantically enrich an as-is BrIM to meet the difficulty of producing correct IFC model representations of bridges that contain structural damage information derived from PCD. For the generation of as-is BrIM, tools and techniques based on IfcOpenShell, point cloud and CloudCompare software were employed. Semantic enrichment involved integrating damage data detected in the point cloud while complying with BMS classifications and IFC schema. BMS damage classifications included damage type, degradation mechanism, damage location, and damage severity. Regarding the IFC structure, the authors employed a set of existing entities, including IfcSurfaceFeature (for damage geometry), IfcPropertySingleValue, inherited from IfcPropertySet (for damage type and severity), and IfcTask.

Delgado et al. [34] employed IFC4 as a basis for modelling the bridge monitoring system in Autodesk Revit. The authors intended to visualise sensor data directly into BIM models. As this IFC version did not consider any type of structural sensors, they used proxy entities and user-defined property sets to enable basic interoperability in the BIM environment. Proxy entities serve as placeholders for elements without predefined classes in the BIM schema [18, 36]. Despite potential data exchange concerns, numerous studies have employed proxy entities for flexibility in representing elements and geometric comprehensiveness (see, for instance, [17, 29, 34–36]). Based on IFC4 Add2, Sacks et al. [17] proposed a Semantic Enrichment Engine for Bridges (SeeBridge) to tackle challenges related to the automatic identification of bridge components from point clouds and the semantic enrichment of these components, including the detected anomalies. The SeeBridge approach incorporates advanced remote sensing technologies, including 3D geometry reconstruction, semantic enrichment, defect detection, and evaluation. The approach was supported by the Model View Definition (MVD) for semantic enrichment and the Information Delivery Manual (IDM) for specifying user requirements.

Jeong et al. [62] extended the OpenBrIM schema to foster data exchange and information integration in bridge monitoring and management systems. They created new data entities to store information required for sensor descriptions, structural analysis, and bridge monitoring. In defining these data entities, the authors evaluated objects from software like CSiBridge for structural modelling, and the Sensor Model Language (SensorML) standard. For example, regarding structural modelling, the "node" entity in OpenBrIM lacked the necessary parameters for defining a reference coordinate system. To address this, they added a new object, the FECoordinateSystem, containing information about the coordinate type and the origin of the reference system.

Bringing together the findings from Sects. 4.2.2, 4.2.3, and 4.2.4, this subsection contributes to fully answering RQ2. Three as-is BrIM model generation approaches were identified and classified under Group I (cloud-based approaches), Group II (parametric and data-driven approaches), and Group III (hybrid approaches and other methods). The review of modelling strategies indicates that point cloud-based approaches are the most widely adopted, whether used solely or combined with other methods to form hybrid approaches, while parametric and data-driven methods are gaining traction. Despite their potential, all methods face challenges, including achieving semantic enrichment and ensuring interoperability throughout the bridge lifecycle, albeit at varying difficulty levels for each method. Addressing interoperability challenges is crucial to ensure a seamless transition from simple 3D digital models to fully BrIM model implementations. This involves leveraging open standards such as IFC and OpenBrIM, as well as expanding associated schemes to include bridge-specific components and structural monitoring data. Approaches such as ontologies, IfcPropertySets, and Semantic Web Technologies are increasingly being utilised to address these issues.

4.4 From BrIM to BDT for Structural Performance Monitoring and Management

4.4.1 Overview of BrIM-Based BDT

BrIM (as part of BIM) has been recognised in the construction industry, particularly within the bridge sector, as a key technology from which a BDT can be developed [6, 20, 23, 24, 55, 94, 112, 114, 129], despite significant challenges related to technological integration, standardisation issues, and the early stages of BDT technology [6, 23, 24, 112]. The overlap of these technologies is becoming a new topic of study, gaining increasing interest from researchers and practitioners [125]. Despite their close relationship, it is essential to note that BDT is distinct from BrIM. A thorough comparison of the two technologies can be found in the study conducted by Yang et al. [24].

BrIM and BDT development have a close relationship for several reasons. According to Costin, Adibfar and Bridge [23], BrIM provides three key aspects of BDT: (i) 3D geometry; (ii) data concerning physical objects; and (iii) process-related data. Honghong et al. [6] state that BIM is now well-established, with multiple standards and application technologies that are both flexible and extensible. BrIM is following the same path, with new technologies being constantly adopted to enhance it, potentially serving as an entry point to the development of BDT. Vassilev, Laska and Blankenbach [94] and Martens, Blut and Blankenbach [82] suggest that constantly updating and semantically enriching BrIM models with information, such as inspection, maintenance, or monitoring data, can evolve these models into functional BDTs.

A BrIM-based BDT builds upon BrIM and other existing technologies [23], but its main value is the knowledge acquired through integrating BrIM with many other information sources [23]. This integration improves performance monitoring and management with enhanced functionality, improved visualisation, and various data streams [23]. Various technologies and systems have been identified in the literature as vital for merging with BrIM to create a functional BDT. These include FE modelling and SHM [6, 20, 23, 24, 27, 112, 114, 115, 126], VR/AR/MR [6, 20, 23, 24, 118], GIS [23, 24], reality capture systems [6, 20, 24, 112], the IoT [6, 20, 23, 24, 27, 88, 112, 115], cloud computing and wireless communication [6, 23, 24, 112], and AI/ML [6, 20, 22–24].

Like the broader DTs, BDTs are naturally multifaceted, and theoretically, they can contain extensive information about the physical bridge [23]. However, as observed by Costin, Adibfar and Bridge [23], it is not practical for a BDT to include all real-world data. Rather, the focus should be on specific use cases, which define the type, level of detail, and volume of information presented [4, 23]. The maturity of the BDT may also be dictated by this approach [6, 55].

The multifaceted nature of BDT can sometimes lead to confusion with BrIM itself or other structural condition assessment systems, such as SHM [24]. As stated by Costin, Adibfar and Bridge [23], BDTs are characterised by their ability to combine existing technologies and systems into an integrated framework. They use a 3D model to reflect actual bridge conditions and provide real-time feedback on structural health. They may incorporate sources like AI or ML to improve predictive maintenance and preventative measures [20, 22–24].

This overview and the following two Sect. 4.4.2 and 4.4.3 answer RQ3 completely.

4.4.2 Technologies and System Integration

Various software and tools relevant to the SPMM of bridges are now included in different platforms, such as OpenBrIM [77]. While these platforms may aid in BDT creation [55], they are not ideal for direct usage as they are often too generic and may not match the specific requirements of some BDT applications [6]. BDTs are typically designed to enable interaction between the virtual and physical environments, allowing replication of physical effects in real-time [6, 23, 24, 112] or “right-time” [112]. It emphasises the necessity of integrating technologies and/or systems able to respond to specific needs, which is typically a complex process [23]. For instance, BDTs require constant model updates, which may involve FE modelling and data collection through sensors fixed on the bridge [23], or other means, such as UAVs equipped with LiDARs or cameras for continuous data collection [23, 24].

Regarding technology and system integration, following the approach by Honghong et al. [6], the BDT development may be viewed from three perspectives: (i) data gathering, transmission, and storing; (ii) data processing, application and integration; and (iii) data representation (visualisation).

- **Data gathering, transmission, and storing:** Bridge data is often collected through sensors [4, 6, 23, 24], which may incorporate an IoT network to enable real-time data transmission to databases through specific communication channels [4, 6, 23]. UAVs equipped with LiDAR or cameras have also been employed to capture bridge damage data [23, 24]. However, they tend to focus more on the external aspects of the bridge rather than the gradual degradation of material properties [24]. 5G, optical fibres, and high-speed Wi-Fi are examples of communication technology [24]. The collected data is stored in databases for subsequent processing, sharing and integration. Well-known databases include CDE (standardised in BIM) [24], NoSQL and DynamoDB [55, 118], and Microsoft Azure [27, 55].
- **Data processing, application and integration**: This part, also connected to a database (such as previously mentioned), involves modelling and includes the BrIM model linked to other models or systems. These may include analysis models (e.g., FE modelling and AI/ML-based analysis models) and related software programs that enable simulations and other operations. For example, for simulation, software programs suggested in literature include Ansys [6, 27, 115], Abaqus [6], Diana [114], Midas [112], and Matlab [115].
- **Data representation (visualisation):** While BIM/BrIM platforms may be used for structural performance visualisation [115], there is also a rising interest in high-dimensional visualisation data, which enhances user-

computer interaction experience [6]. VR, AR and MR technologies, supported by software like Unity [6, 112, 118], while currently insufficiently explored in the reality of bridges [24], are increasingly being recognised as promising solutions for such purposes [6, 20, 23, 24].

As already stated, the technologies or systems included in a BDT developed from BrIM may vary depending on specific use cases or the complexity involved [4, 23]. For instance, Sun et al. [115] developed a BDT by integrating BrIM, FE modelling, and IoT. BrIM centralised data integration and visualisation, whilst the FE model performed real-time structural analysis using IoT sensor data. The system merged model-based simulations with real-time data, with Python programming enabling the exchange of information across Matlab, Ansys, and Revit software. Armijo and Zamora-Sánchez [27] employed a similar technology combination to develop a BDT for SHM of railway bridges with low-cost wireless accelerometers. Chacón et al. [112] proposed combining BrIM with multiple technologies, including FE modelling, IoT, and VR, to create a BDT for assessing bridge conditions utilising load testing. Revit, Grasshopper and Rhino.Revit were used to generate the BrIM model and prepare the structural graph. Midas software was used for extensive structural simulations, with Unity serving as the major visualisation platform, connecting BrIM, real-time IoT data and Midas-generated simulations through APIs. John Samuel et al. [118] proposed a BDT approach that combines BrIM, reality capture technologies, and AR to improve bridge inspection and monitoring. AR was utilised to overlay virtual defects over real-world structures during inspections, and robots and drones captured necessary data that was integrated into the BrIM model and made available to field users via mobile application.

Table 8 provides an overview of the combination of BrIM with different technologies or systems for BDT creation reported in the literature. It only contains studies that mainly discuss a combination of BrIM (even when not explicitly referred to as BrIM) with other technologies or systems, and the tools and software employed. Most studies emphasise the use of a common database, often cloud-based, for both data storage and sharing. Cloud databases mentioned include CDE [6, 20, 24, 27, 112], NoSQL [118], DynamoDB [118], On-premises [27], and Microsoft Azure [27].

Frequently, IFC is employed to connect the BrIM model to other models, like those used for structural analysis or visualisation/user-interaction systems [6, 27, 112, 114, 118]. Additional useful tools for integration include Python programming [115], APIs such as Dynamo and Grasshopper [20, 23, 112], and ontologies [6]. In real-time interaction between the physical and virtual environment, IoT (e.g., integrated with sensors) and internet-based communication are often required for data collection and transmission. In some studies, while the concept of technology and system integration is discussed, specific technologies (e.g., type of software or tools) are not always detailed. Nonetheless, most studies in Table 8 include a case study rather than just a framework, indicating that real-world BDT implementation is increasingly becoming more probable.

In summary, this discussion contributes to answering RQ3, particularly regarding the technological requirements for BrIM-based BDT development. The essential technological components include: data gathering, transmission, and storage; data processing, application and integration; and data visualisation/user interaction. Achieving a fully functional BDT requires integrating multiple technologies, yet challenges remain in several issues, as detailed in next Sect. 4.4.3.

4.4.3 Brief Description of Barriers and Challenges in Technologies and Integration

Several barriers and challenges to BDT adoption have been extensively reported in the literature (see, for instance, [6, 23, 24]). This subsection focuses on the technology and integration barriers and challenges crucial in answering RQ3. Technology-related issues and system integration are frequently mentioned in the literature as the primary challenges to successful BDT implementation [21, 24, 112]. As outlined in Table 9, these barriers and challenges span multiple categories, including: (i) Interoperability and lack of unified platforms; (ii) Sensor, IoT integration, and real-time performance; (iii) Reliability and accuracy of model updating; (iv) Advanced data analytics and AI/ML integration; (v) Data visualisation complexity; (vi) Cost and data privacy; and (vii) Skill gap.

- **Interoperability and lack of a unified platform:** Integrating multiple technologies and data sources is a significant challenge owing to the lack of a unified platform [10, 23, 112]. Existing software frequently enables the generation of individual models rather than a whole BDT [6]. Furthermore, many key software and related data lack compatibility [21, 55], complicating integration efforts. Suggested solutions for software and data linkage include the use of APIs [23, 112], ontologies [6, 21], and open data exchange standards and SWT [21, 23].
- **Sensor, IoT integration, and real-time performance:** Connecting physical and virtual bridges rely primarily on IoT, web communication, and sensor data integration [4, 27, 74, 112, 115, 129]. IoT devices enable real-time data access [4, 27, 74, 115], and it is also common for IoT devices to be integrated with sensors (also referred to as IoT sensors) [27]. However, while sensor and IoT integration is crucial for BDT, studies have revealed data collection and transfer issues, including inconsistent sen-

Table 8 Reported technologies and systems combined with BrIM in BDT development

References	Data gathering, transmission, and storing		Analysis models and others integrated in BrIM		Visualisation/user interaction		Tools for BrIM integration	Framework (FW) or case study (CS)
	IoT/sensors/ reality capture/web-communication/cloud computing	Specific tool/software mentioned	FE modelling/AI/ML-based analysis and others	Specific tool/software mentioned	VR/AR/MR; BIM/BrIM platform; and others	Specific tool/software mentioned		
Honghong et al. [6]	Included	3G-5G; OFTS; WIFI; CDE	Included	Ansys; Abaqus	Included	Unity	Ontologies; CDE; IFC	FW
Costin, Adibfar and Bridge [23]	Included	video-camera; ITS; IoT- sensors	Included	GIS—ArcGIS	Included		APIs	FW
Hosamo and Hosamo [22]	Included	WSN; drone	Included					FW
Yang et al. [24]	Included	4/5G mobile; FBG sensors; accelerometers	Included		Included		CDE	FW
Chacón et al. [112]	Included	Mainflux-IoT platform; MQTT, Web-Socke	Included	Midas	Included	Unity	CDE; IFC; API -Grasshopper	FW + CS
Jasiński et al. [20]	Included		Included		Included		CDE; API—Dynamo; SOFiSTiK	FW + CS
Tita et al. [114]	Included	GNSS satellites	Included	Diana	Included	BIM platform	IFC	FW + CS
Sun et al. [115]	Included	video-camera; set of sensors with IoT (displacement transducers; inclinometers; strain gauges; accelerometers)	Included	Ansys; Matlab	Included	BIM platform-Revit	Python programming; IFC	FW + CS
Kaewunruen et al. [129]	Not included (manual data collection)				Included	BIM platform-Revit and Navisworks		CS
John Samuel et al. [118]	Included	DynamoDB; NoSQL			Included	BIM platform-Revit; Unity;	DynamoDB; APIs IFC; FBX;	FW + CS
Armijo and Zamora-Sánchez [27]	Included	IoT sensors-accelerometers MQTT; 4G/5G networks; MLflow; Microsoft Azure; On-premises	Included	Ansys; LightGBM ML classifier	Included	BIM platform-BIM viewer	CDE; IFC;	FW + CS

Table 8 (continued)

References	Data gathering, transmission, and storing		Analysis models and others integrated in BrIM		Visualisation/user interaction		Tools for BrIM integration	Framework (FW) or case study (CS)
	IoT/sensors/ reality capture/web-communication/cloud computing	Specific tool/software mentioned	FE modelling/AI/ML-based analysis and others	Specific tool/software mentioned	VR/AR/MR; BIM/BrIM platform; and others	Specific tool/software mentioned		
Adibfar and Costin [21]	Included		Included	AI-based algorithms	Included	BIM platforms-Revit; Bexel Manager; and Solibri	API—Dynamo; IFC; Excel	FW + CS

ITS intelligent transportation systems, *WSN* wireless sensor network, *OFTS* optical fiber transceiver system, *FBG* fiber bragg grating, *NoSQL* non-structured query language, *FBX* Filmbox, *MQTT* message queuing telemetry transport

sor outputs [21] and bandwidth constraints, especially when multiple sensors are involved [4]. These integration hurdles frequently result in offline data transmission and processing, limiting real-time capability [4, 115].

- **Reliability and accuracy of model updating:** BDTs for SPMM typically combine an as-is 3D model (or BrIM model) representing bridge geometry with a mechanical model, generally an FE-based model [10, 114, 115]. As already discussed, other technologies or systems may also be integrated, depending on the scope and specificity of BDT. The literature reports challenges in updating the geometric and FE models simultaneously and automatically [4, 24]. These challenges arise from multiple factors: the inverse nature of FE model updating, where updated parameters may be derived from structural response data obtained from experiments/sensor measurements [4, 24] and the necessity of verification and validation to ensure that the updated FE model accurately reflects the actual bridge structure [10]. Consequently, complex adjustments often require human intervention [4].
- **Data visualisation complexity:** While data visualisation is one of the critical benefits of BDT [6, 24, 114, 129], achieving it remains challenging, mainly due to the variety of advanced technologies required [24]. Once more, a lack of a unified platform and interoperability amongst the systems and software hamper the process.
- **Advanced data analytics and AI/ML integration:** Another notable limitation of existing BDT implementations is the deficiency of AI/ML integration [6]. For instance, Honghong et al. [6] highlight challenges with numerical simulations, which frequently struggle to effectively depict complex multi-load scenarios in structural analysis, resulting in computing delays hindering real-time assessments. Integrating AI/ML might considerably reduce these issues by improving both modelling accuracy and speed.
- **Cost and data privacy:** Implementing BDTs is also hindered by some cost-related issues. Chacón et al. [112] note the costly expenses of data integration, while Lu and Brilakis [68] highlight that bridge owners frequently disregard BDTs for existing bridges due to cost concerns. Sakr and Sadhu [4] and Armijo and Zamora-Sánchez [27] draw attention to the financial issues of maintaining sensors for long-term monitoring, which is essential to BDTs. According to Armijo and Zamora-Sánchez [27], structural monitoring systems are often limited to a few bridges of special interest. John Samuel et al. [118] argue that modern problem-solving technologies are frequently costly, sometimes challenging to use, and do not necessarily result in reliable outcomes. Additionally, data privacy concerns, such as preserving proprietary technologies, hinder the open sharing of practical applications [4].

Table 9 Barriers and challenges in technologies and integration for BDT implementation

#	Category of barrier and challenge	References
1	Interoperability and lack of a unified platform	[6, 55, 112, 112, 130]
2	Sensor, IoT integration, and real-time performance	[4, 6, 115, 115]
3	Reliability and accuracy of model updating	[4, 10]
4	Data visualisation complexity	[24]
5	Advanced data analytics and AI/ML integration	[6]
6	Cost and data privacy	[4, 23, 27, 55, 68, 112]
7	Skill gaps	[4, 23]

- **Skill gaps:** Like many emerging technologies, BDT encounters reluctance to change, exacerbated by a considerable skills gap [4, 23]. The workforce is often unfamiliar with emerging technologies such as BDT, particularly modelling and other advanced applications. As BDT is a multi-technology approach, it requires expertise in various domains, including engineering for software, engineering for structures, management, and equipment specialism [4].

Building upon the discussions in Sects. 4.4.1 and 4.4.2, this subsection fully answers RQ3 by summarising the state-of-the-art of BrIM integration with structural monitoring systems, along with different emerging technologies for BDT development. The primary barriers and challenges to full BDT implementation include, among others, interoperability constraints and the lack of a digital unified platform, real-time data processing limitations, data visualisation complexity, and skill gaps. Addressing these barriers and challenges will be critical to realising the full potential of DTs in bridge asset management.

5 Conclusions

This SLR provides a comprehensive analysis of the transition from BIM to BrIM, and ultimately to BDT, focusing on SPMM. By addressing the three primary RQs, the review provides insights into how these technologies are employed and the challenges and limitations related to their full implementation. From an initial set of 3459 articles retrieved from a query of academic databases, 152 were assessed and classified manually, and 128 of these were selected for full content review.While BrIM is explicitly intended for bridge infrastructure, it is not as widely adopted as BIM for buildings. However, significant progress has been made, including the release of IFC 4.3, and a number of continuing initiatives to enhance interoperability. In relation to RQ1, about the current state of BrIM and its transition from BIM, numerous key progress segments and current challenges were identified:

- **Interoperability progress through IFC**: Significant interoperability advances have been achieved as a result of continuous upgrades to IFC standards, most recently with the release of IFC 4.3, which now incorporates bridge components.
- **OpenBrIM as a supplementary solution:** OpenBrIM emerged as a valuable alternative to BIM, to address some of the current limitations in BIM standard. Its cloud-based platform now supports IFC-based workflows, allows integration with certain software applications, and provides further compatibility with 2D and FE model transfers.
- **Challenges during the operational phase**: Incorporating structural performance monitoring data, such as sensor readings, into digital models is one of the primary challenges in BrIM. Despite advances in IFC and OpenBrIM, current methods struggle to handle real-time performance data, indicating the necessity for new open-standard data models to enable structural performance monitoring systems.
- **Addressing gaps in current Standards**: A number of studies have highlighted gaps in current IFC implementations. Accordingly, it was observed that certain studies tend to use building-oriented BIM platforms for bridge models generation without making the necessary adjustments throughout the modelling process, which frequently results in poor LoD of respective BrIM models. IFC entity extension, use of IFC property set and proxy entities to represent components not covered by current standards are some of the solutions that have been suggested. Innovations such as ontologies and data dictionaries also offer promising possibilities in bridging these gaps, as they help improving interoperability and semantic richness.

The review also looked at different strategies for generating as-is BrIM models (RQ2), categorising them into three groups: (i) point cloud approaches, (ii) parametric and data-driven approaches, and (iii) hybrid approaches and other methods. The following points highlight the main findings:

- **Dominance of point cloud approaches:** Point cloud approaches were found to be the most commonly used techniques in 3D digitisation. However, they frequently fall short of producing fully detailed BrIM models, as they are typically limited to generating simple 3D geometric representations (with this occurring more when photogrammetry is used). These approaches tend to be more effective when paired with additional approaches, such as classical direct modelling, forming a hybrid approach.
- **More traction to parametric and data-driven approaches:** Parametric and data-driven approaches are gaining traction in modelling processes, showing a trend towards more efficient methods for developing detailed models of existing bridges. While parametric approaches provide flexibility and iterative adjustments, they require a large amount of input data, which can occasionally result in inaccuracies in the finished 3D/BrIM model.
- **Hybrid approaches for comprehensive modelling:** combining different methods, such as classical direct modelling and point cloud, is currently an efficient solution for producing comprehensive as-is BrIM models. However, some combination may lead to significant time consumption, if not applied strategically.
- **Ensure long-term digital sustainability:** maintaining and updating BrIM models throughout a bridge lifecycle is critical. The adherence to open standards and robust procedures is the key to the long-term viability of these models.

Lastly, in order to address RQ3, the review analysed how BrIM is integrated with different technologies and systems for creating BDTs. These technologies and systems span the domains of data collection, transmission, processing, and visualisation when coupled with BrIM. Notwithstanding significant advances, a variety of technological challenges and barriers remain. The key insights are as follows:

- **BrIM as a basis for BDT development:** BrIM models offer detailed 3D geometry and process-related data required for BDT development. The incorporation of technologies and systems such as FE models, wireless communication, IoT, cloud computing, AI/ML, and AR/VR/MR into BrIM allow the transition to BDTs, enhancing SPMM and real-time operations.
- **Technology integration solutions:** Integrated solutions leverage cloud databases, APIs, open standards like IFC, and ontologies, in an attempt to unify diverse technologies and systems, such as BrIM, SHM systems, and VR/AR/MR.
- **Technology integration challenges:** Integrating multiple technologies and ensuring reliable real-time data transmission and visualisation are key challenges to BDT development. Manual verification is sometimes required when updating BrIM and FE models with real-world data, which limits automation. While AI/ML integration shows promise, there are still issues for their effective integration. Financial restrictions and skill gaps in advanced modelling are also important barriers to BDT adoption.

This review shows that the continual advancement of BDT and BrIM technologies is critical to the future of bridge infrastructure management in general, and structural performance monitoring in particular. These digital tools have the power to revolutionise bridge management and offer future infrastructure solutions that are safer, smarter, and more sustainable, as long as sufficient focus is placed on overcoming the current constraints.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing interest On behalf of all authors, the corresponding author states that there are no conflicts of interest associated with this work.

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