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Review

Strategic alignment of BIM and big data through systematic analysis and model development

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ABSTRACT

Organisations increasingly rely on data-driven strategies, utilising analytics to achieve competitive advantages. This paper systematically investigates the integration of big data into Building Information Modeling (BIM) within the Architecture, Engineering, and Construction (AEC) sectors, named “big BIM data.” Employing mixed methods of systematic and bibliometric analysis, it synthesises findings from 125 records published 2013–23. While many studies are at preliminary stages with conceptual or small-scale experimental approaches, the paper categorises its results into four domains: AEC organisational infrastructure, big BIM data (IT) infrastructure, AEC organisational strategic domain, and big BIM data (IT) strategic domain, aligned with the Strategic Alignment Model (SAM), exploring organisational competencies, governance factors, and strategic frameworks. This paper introduces the AEC Organisational - Big BIM Data SAM as the research agenda to implement big BIM data utilisation across AEC industry. This framework thoroughly addresses organisational dynamics while emphasising interconnectedness among individual projects, organisational tiers, and industry-wide standards.

1. Introduction

Assets are economic resources possessing value and convertible to monetary form. Data, acknowledged as an enterprise asset, requires evolving comprehension in its management [32]. Building Information Modeling (BIM), particularly project and asset information model, serves as a centralised repository accommodating graphical, alphanumeric, and documentation datasets linked to construction projects and assets across its’ lifecycle. In today’s Architecture, Engineering and Construction (AEC) landscape, organisations use BIM to enhance decision-making and operational efficiency [34,108] and drive their digital transformation objectives [90,126]. Consequently, the increasing reliance on data emphasises the substantial value embedded within data assets and their return on investments [11,99]. Many organisations embrace a ‘data-driven’ approach to remain competitive, favouring data-triggered decisions supported by analytics over instinct-based judgments [31,50,67]. This shift towards data-centricity [12] underscores the importance of efficient data management through a blend of business leadership and technical expertise.

Nevertheless, the advancements in mobile devices, internet of things (IoT), digital sensors, communications, computing, and storage have revolutionised data collection [19,120]. This has led to an exponential increase in data volume, diversity (ranging from structured to unstructured formats like documents, files, audio, video, and real-time streaming data), and its velocity of generation within the AEC sector [9,15]. The advent of big data and its supporting technologies has significantly empowered data scientists, enabling them to create predictive models, employ machine learning algorithms, and develop prescriptive analytic models to explore data patterns and by doing so, enriching the so called “enterprise asset” [15,44,58].

These integrated approaches enable them to derive insights and predict behaviours based on large-scale big datasets and parametric mechanisms [63]. In essence, data science has revolutionised data analysis, discovering novel methods to extract value from information. This has sparked many discussions and generate a trail of studies within the AEC sector regarding the potential of using BIM as an information management platform alongside big data and other complementary technologies to elevate productivity and efficiency in the construction industry [10].

This study addresses several gaps in the existing literature. Previous

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research acknowledged the limited availability and accessibility of relevant studies, with Ali and Bandi [3] database yielding only 43 records. By expanding the search criteria, this study increases the dataset to 125 records, providing a more comprehensive analysis. Additionally, this study applies the PRISMA framework for the systematic literature review (SLR), which was not employed in the earlier work.

Moreover, this study addresses gaps overlooked by the existing literatures identified through the SLR, particularly the dynamic and rapidly evolving nature of the AEC organisational environment [14,45]. While current studies highlight the potential applications of BIM and big data, they failed to consider the broader role of "big BIM data" within AEC business operations. AEC businesses, like others, need to align their business strategies with technological innovations, particularly big BIM data, to effectively support and enhance organisational objectives, rather than the reverse.

This gap is evident in the discrepancies found in the works of Ali and Bandi [3] and Ali and Bandi [4]. Although their studies are complementary, with one offering a theoretical framework and the other empirical evidence, they contradict each other regarding the correlation between operation and maintenance (O&M) data and big data attributes. This contradiction may stem from a lack of alignment between an AEC organisation's strategy and the technological demands of higher BIM maturity levels. Additionally, the slow adoption of advanced BIM capabilities, particularly in O&M data integration, can lead to inconsistencies between theoretical models and practical applications.

Ultimately, this study aims to evaluate the current state of big data within the BIM landscape, identify emerging trends, and highlight opportunities for AEC organisations that currently lack expertise in this area. Additionally, it focuses on 3 main areas within the big BIM data research domain; the strategic value that big BIM data brings to AEC business management, the integration into technical IT and managerial domains, and the strategies for effectively aligning big BIM data technology within AEC organisations. The study is structured into six sections, as shown in Fig. 1.

The first two sections introduce the concept of big data and its emergence within the BIM landscape in the AEC context. The third section provides a comprehensive rationale for conducting a systematic literature review (SLR). This section elaborates on the use of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) framework to systematically source, select, analyse, and summarise literature on big BIM data. Additionally, it details the extraction of keywords and construction of a keyword co-occurrence map from titles and abstracts of papers citing BIM and big data, using bibliometric analysis to yield insightful results.

The fourth and fifth sections focus on developing a theoretical understanding of big BIM data by extensively examining findings from the SLR. These sections utilise diverse frameworks and standards, including the Data Management Body of Knowledge (DMBoK), Project Management Body of Knowledge (PMBoK), Asset Management Body of Knowledge (AMBoK), the ISO 19650 series, Strategic Alignment Model (SAM) to formulate robust conclusions. The final section identifies research gaps and sets forth a future research agenda.

2. Background and related works

2.1. Big data definition

Since the 2000s, the terms "Big Data" and "Data Science" have emerged as buzzwords, often misunderstood or left undefined. Despite the ambiguity, these terms represent significant technological advancements that enable the generation, storage, and analysis of vast amounts of data. Distinguishing big data from traditional data involves more than just its volume. According to Hu et al. [48], big data includes several unique features that set it apart from terms like "massive data" and "very large data." Although there is no universally accepted definition of big data, its unique characteristics are broadly recognised. Table 1 illustrates the key differences between traditional data and big data.

Based on the information in Table 1, it is evident that the AEC sector now deals with "big data," a term encompassing the ever-expanding volume of information that organisations store, process, and analyse, driven by the proliferation of information sources [15,17,37,59,103]. Managing big data in the AEC sector presents several distinct challenges, often referred to as the six Vs, and listed in Table 2: Volume, which pertains to the vast amount of data, often involving billions of records; Velocity, the speed at which data is captured, generated, or shared, frequently in real-time, including sensor data from smart buildings and real-time updates from construction sites; Variety, the diverse formats in which data is captured or delivered, such as Autodesk's DWG (Drawing), DXF (Drawing Exchange Format), and Bentley's DGN (Design) for engineering, requiring storage of multiple formats with inconsistent structures; Viscosity, the difficulty of using or integrating data, often

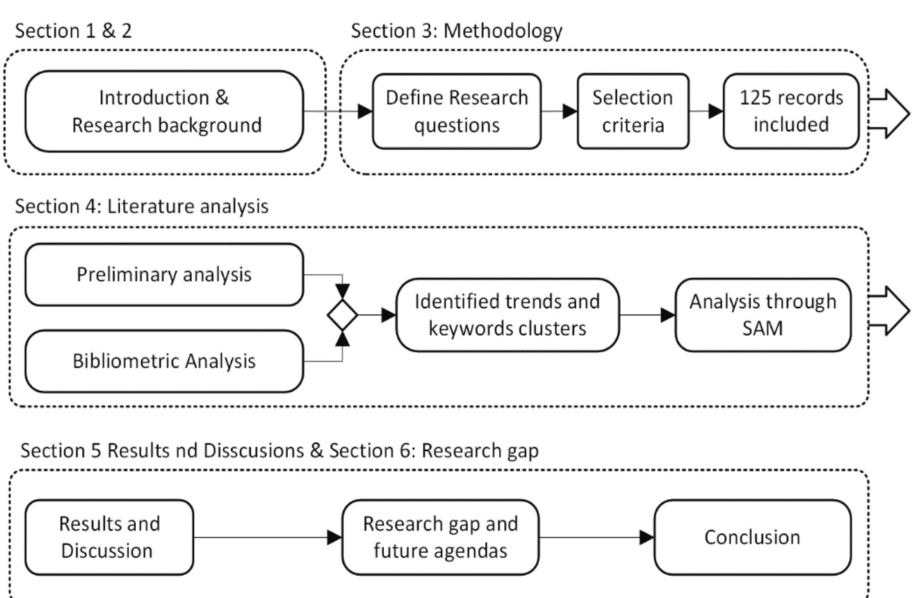

Fig. 1. Research structure.

Table 1
Difference between traditional and big data adopted by Hu et al. [48]; Jain [55].

	Traditional data	Big data
Volume	Typically measured in gigabytes or terabytes.	Measured in petabytes or exabytes.
Velocity (Data flow)	Generated at a relatively slower rate, or in some cases, they are static data.	Generated at an incredibly high rate in real-time or near real-time.
Variety (Data Structure)	Pre-established structures, structured data fitting neatly into a relational database.	Semi-structured or unstructured, diverse data from various sources
Veracity	Trustworthy and reliable	Often noisy, uncertain, and lacks consistency.
Data source	Internal to the organisation; centralised.	Internal and external; distributed.
Data integration	Relational database management system (RDBMS).	Hadoop Distributed File System (HDFS), Non-tabular databases (NoSQL).
Data storage	Interactive	Batch or near real-time.
Type of Analysis	Descriptive; often performed manually or using traditional Business Intelligence (BI) tools.	Predictive or Prescriptive; advanced analytics, including Machine Learning (ML) and Artificial Intelligence (AI), required.

Table 2
Big data 6Vs characteristic and descriptions.

	Description
Volume	Denoting the sheer amount of data. Big Data typically comprises vast numbers of entities or elements across billions of records.
Velocity	Reflecting the speed at which data is generated, captured, or shared. Big Data is frequently produced in real-time and can be rapidly distributed and analysed.
Variety/ Variability	Encompassing the diverse forms in which data is captured or delivered. Big Data necessitates storage and handling of multiple data formats, often exhibiting inconsistencies in data structure within or across datasets.
Viscosity	Signifying the level of complexity or difficulty in utilising or integrating the data.
Volatility	Representing the frequency of data changes, determining the duration of data usefulness.
Veracity	Indicating the reliability and trustworthiness of the data, emphasising the accuracy and credibility of the information

siloed within different departments, making it challenging to create a cohesive project view, necessitating sophisticated integration platforms to overcome; Volatility, the frequency of data changes and the duration of data usefulness, as project conditions in the AEC sector can change rapidly, requiring systems that handle frequent updates without compromising data integrity; and Veracity, the trustworthiness of the data, where inaccurate data can lead to significant errors and delays, requiring rigorous validation, quality control measures, and a culture of data stewardship to ensure reliability [5,32,59].

Although the AEC sector has entered the "big data era," understanding the role of BIM within this landscape is crucial. BIM is often regarded as the "centrepiece" of construction technology, serving as a key enabler and facilitator for various other technologies in the industry [35]. Despite this, a typical BIM model does not usually exceed 100 gigabytes and rarely approaches 100 terabytes, raising the question of whether BIM data is substantial enough to justify the use of big data analytics [28].

However, successful execution of analytical tasks in the AEC sector requires diverse datasets encompassing building design, material properties, and construction domain knowledge, which are often complex, voluminous, heterogeneous, and incomplete [15,17,64]. Traditional technologies struggle to store and process such data in real time for advanced analytics, underscoring the necessity for big data technologies to manage and analyse these extensive datasets effectively. Fig. 2 illustrates a comprehensive overview of the spectrum of data, technology, and applications made accessible by the integration of BIM and big data technologies, along with the resulting implications for data storage solutions.

2.2. A shift towards big BIM data approach

The convergence BIM and big data within AEC organisations is driven by a quest for expanded business opportunities derived from diverse datasets [15]. These extensive data collections foster innovation by enabling predictive models that cater to individual customer needs, facilitating personalised product and service delivery [1,17,80,92,100]. Data science, through machine learning algorithms, further streamlines operations by automating complex tasks, enhancing organisational efficiency, reducing costs, and mitigating risks [1,17,80,92,100].

However, the realisation of big data's potential for generating unique insights and actionable intelligence via BIM relies on adeptly managing extensive BIM datasets. Effectively managing big BIM data, due to its diverse origins and formats, requires more stringent discipline than conventional data management practices [5]. While guiding principles for managing big BIM data are evolving, the handling of metadata among other challenges, associated with big data sources emerges as a crucial aspect. This involves maintaining precise records of data files, their origins, and their intrinsic value within organisational frameworks [5,89].

Given the transformative shift in this paradigm, it becomes imperative to conduct the first comprehensive review of big BIM data within the AEC organisational (business) domain.

3. Methodology

This study employs a mixed-methods literature review to explore gaps and opportunities in the integration of BIM and big data within AEC organisations, guided by the approach of Application Spotting by Sandberg and Alvesson [93]. This method focuses on identifying theoretical and practical gaps in existing literature to enhance our understanding of the subject. The research questions are designed to address these gaps:

- RQ1. What is the current research landscape on the integration of BIM and big data?
- RQ2. What strategic value does big BIM data offer to the strategic business management domain of AEC organisations?
- RQ3. How does the integration of big BIM data impact the technical information technology domain of AEC organisations?
- RQ4. What are the optimal strategies for effectively integrating big BIM data technology in AEC organisations?

The approach combines a Systematic Literature Review (SLR) for qualitative insights and a Bibliometric Analysis (BA) for quantitative data analysis. The mixed-methods literature review in this study is justified for its ability to provide a comprehensive and validated understanding of the integration of BIM and big data in AEC organisations. SLR with BA, the study gains both qualitative insights into individual research studies and quantitative data on research trends and relationships. This approach enhances the study's depth by triangulating findings from different perspectives, validating qualitative insights with quantitative measures such as keyword co-occurrence [20,43,94]. It also allows for a thorough exploration of emerging themes and influential studies through techniques like science mapping, which visualises patterns across a large body of literature [39,46,95].

3.1. Systematic literature review

To address the research, aim and questions, a systematic literature review was selected as the most appropriate method to explore big data within the BIM landscape. This approach enables the identification of

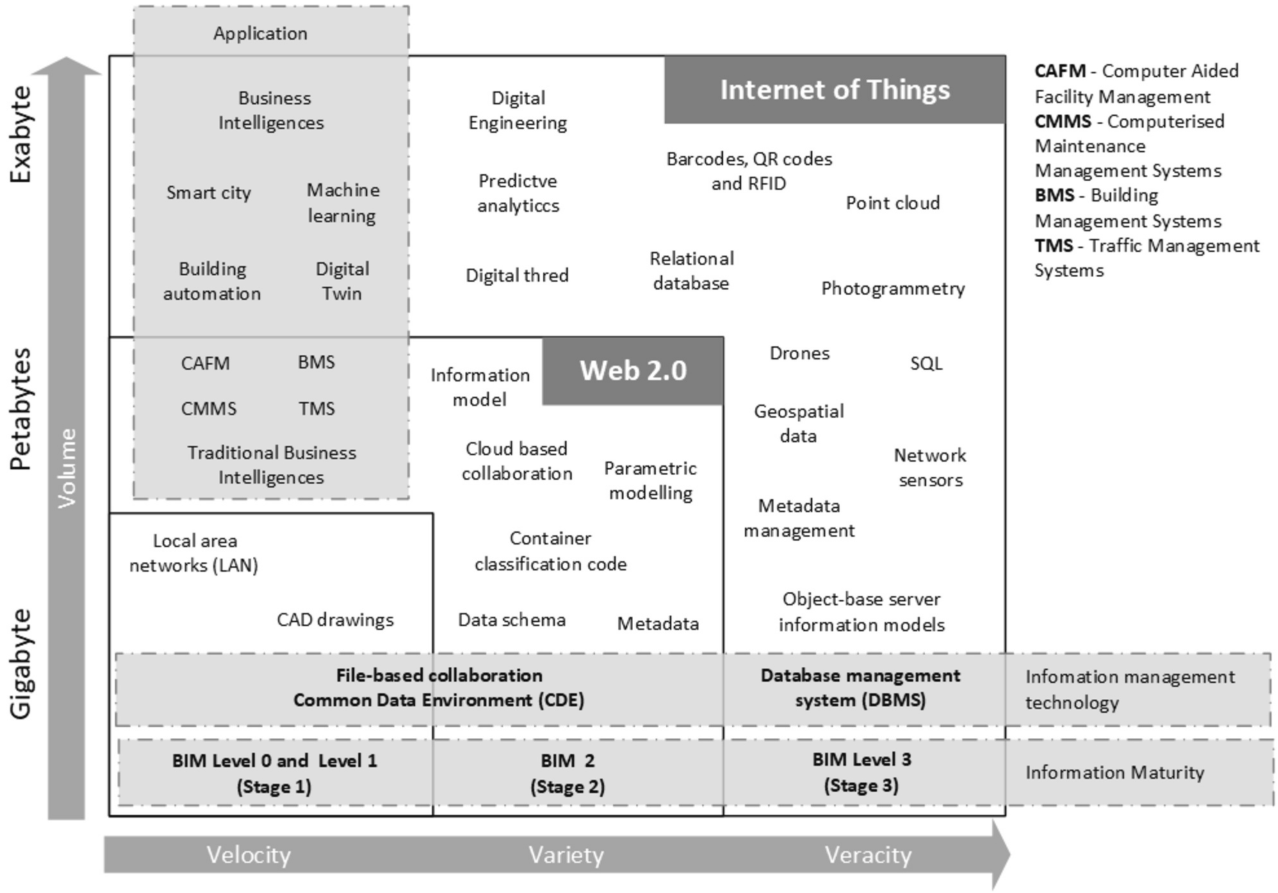

Fig. 2. Data, Technology, and Applications enabled by the integration of BIM and big data adopted from [32] and ISO19650-1 [54]: Information maturity model.

ongoing trends, examination of existing applications, and delineation of potential opportunities for AEC organisations that have yet to adopt this technology.

The SLR was performed following the PRISMA framework [78]. The SLR was conducted with explicit methodologies and their underlying philosophies and paradigms, developed the entire protocol beforehand to ensure a rigorous and consistent approach. However, as the process unfolded, new factors and aspects emerged, leading to various clarifications and amendments made to the initial documentation and protocols over the course of the study. Nonetheless, the findings from previous studies are presented in a clear and chronological order aligning with the SAM. In this study, the SLR was conducted by defining selection criteria, data sources, and a search strategy. The criteria for analysis and synthesis were also established, followed by a description of the data collection process and the use of data extraction forms. The sequence of the SLR activities is illustrated in Fig. 3.

3.1.1. Data sources and search strategy

To begin the search protocol, electronic databases including Scopus, Web of Science, IEEE, Science Direct, and Google Scholar were used with the search strings listed in Table 3. These databases were chosen for their comprehensive coverage of scholarly literature, relevance to engineering, technology, and construction, and high-quality sources. The integration of databases such as IEEE and Science Direct ensures coverage of both theoretical and applied research, supporting an interdisciplinary approach to understanding BIM and big data. This ensures a thorough, high-quality, and multidisciplinary review of the existing literature on BIM and big data.

The initial search spanned from the early 2000 to the finalisation date of this study, marking the early efforts to define Big Data by Laney [65]. However, the BIM research community began to adopt and see significant advancements much later, around 2013 [24]. Since there was no prior research into big BIM data before 2013, this study defines the timeframe as 2013 to 2023 and was not restricted to any specific country, ensuring a comprehensive and up-to-date analysis of global developments in the field.

Two authors independently retrieved the titles and abstracts of primary studies from an electronic search. Recognising the importance of Big Data and Big Data Analytics across various disciplines, the search was limited to construction literature for focused and meaningful inferences. A total of 579 records from sources including journals, conference proceedings, dissertations, and PhD theses were identified.

While conducting the search, the keywords in Table 3 were grouped together by using truncation characters (e.g., ‘*’, and ‘?’), Boolean Logic Operators (including AND, OR), phrase searching, and parentheses. The final search string was constructed iteratively by using the following steps. First, relevant articles were searched for the BIM, Big data, and construction discipline. The search strategy explicitly looked for relevant studies that include the discipline’s synonyms (related terms) or the enabling technologies (narrower terms) in the publication’s title, abstract or keywords, see Table 4.

3.1.2. Selection criteria

Layers of inclusion and exclusion criteria were defined to assess the relevance of each publication found. Two authors independently extracted data and evaluated the quality of the literature. The discussion between the two authors resolved disagreements. In the event that the two authors could not come to an agreement, a secondary supervisor (the third author) intervened until a consensus was made. Subsequently, all the included papers were carefully reviewed to extract and code the data. No automation tools were used during this process.

First, the resulting articles should fulfil 6 inclusion criteria related to

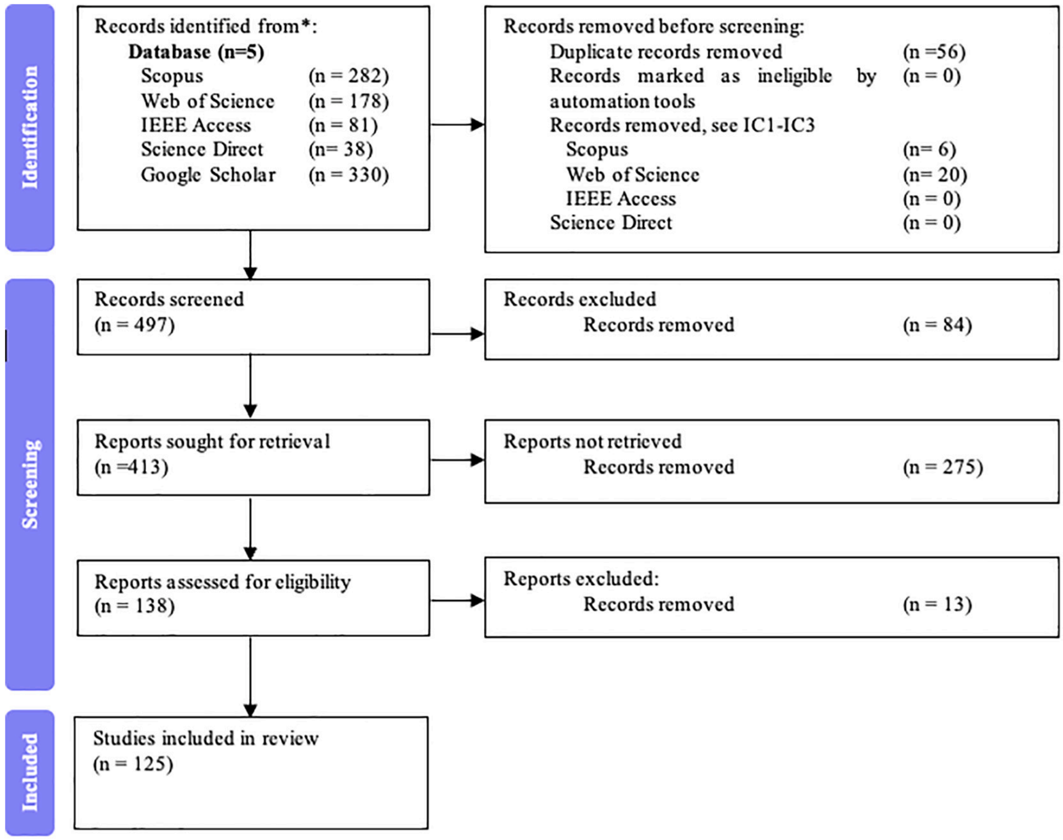

Fig. 3. Process of data collection and analysis for the systematic review [79].

Table 3
Search strings protocol.

TITLE-ABS-KEY	[Building Information Modeling (Related terms) **OR** (Enabling technologies)] **AND**
TITLE-ABS-KEY	[Big data (Related terms) **OR** (Enabling technologies)]

Table 4
Selection of relevant keywords.

Keywords	Related terms	Enabling technologies
BIM	Building Information modeling; Building Information modeling; Virtual Building; Virtual Design and Construction; VDC; 4D BIM; 5D BIM; 6D BIM; nD BIM, Asset management	N/A
Big data	Big data; BD; Big data Analytics; Massive Data; Mass Data; Large Data; Enormous Data; Big data Analytics; Big Analytics; Massive Data Analytics; Mass Data Analytics; Large Data Analytics; Enormous Data Analytics: Linked opened data; Database; DBMS	Data Management; Data Driven; Data Mining; Data warehouse; Data Lake Process; Mining; Data driven: Knowledge Discovery; Knowledge management

the document type itself:

1) *The articles should be fully published and written in* ***English.***
2) *The articles' subject areas must align with the academic fields taken into consideration (*e.g., *Computer Science, Big data, Construction management, Decision Sciences, and Business Management). The Multidisciplinary category was also included since we are explicitly looking for linkages between the BIM, Big data, and Construction research areas.*
3) ***Only academic document*** *types were included to obtain validated concepts only (*e.g., *articles, books, book chapters, conference papers, and review articles).*
4) *The agenda of the articles must include the development of methods and/or solution that* ***make sense of all real-world data.***
5) *The articles must offer insights of significant value to critical real-world decisions for current or future practice.*
6) *The technology's* ***benefits should be stated explicitly*** *by either: (a) indicating which performance indicators are improved; (b) proposing an architectural design; (c) referring to a specific use case.*

The second layer consisted of the exclusion criteria only. These criteria were implemented to assess the articles' uniqueness. At this stage, the title, abstract, keywords, authors' names and affiliations, journal name, and year of publication of the identified records were exported to Endnote 20 and screened. In this stage, 34 articles were discarded.

7) ***Remove all duplicated*** *articles that consider the same case study; only the most recent version was saved for further reading.*
8) *Remove the article if the proposed technology itself is improved only* ***without specifying any application or providing any empirical evidence.***
9) *Remove the articles that the proposed technologies do not* ***apply to the built environment or construction industry****, including the enhanced decision-making and/or create competitive advantages.*

The remaining articles were downloaded for full-text reading. However, it is possible that the article is not publicly available, or the content is insufficient for further analysis. Therefore, the final layer included three additional criteria to increase the opportunity that the selected articles are actually found. A total of 34 articles were eliminated in this round.

10) *The article* ***should be available online*** *(open access or through a subscription).*
11) *If the article is* ***not publicly available****, the following procedure is executed: (a) To request full-text permission from the article's first author; (b) In case of a negative response, search for another article of the same author(s) that covers the same topic (the article must comply with the other layers of inclusion/exclusion criteria); In case of no results, remove the article for full-text reading.*

A systematic review of the big BIM data landscape is essential to address the increasing complexity, including the volume, velocity, variety/variability, viscosity, volatility, and veracity of data within the AEC industry, collected, generated, managed, and stored using BIM-based technologies. This study goes beyond merely examining technology in isolation; it also considers the broader AEC organisational context by considering and aligning with business goals, scopes, needs, and market value.

By integrating big data within the BIM landscape through a strategic alignment approach, this study ensures that AEC organisations can better meet business needs, enhance decision-making using big BIM data technologies, and gain competitive advantages. This structured approach translates systematic review findings into actionable insights and strategic recommendations, enabling AEC organisations to effectively leverage big data in their BIM practices.

3.2. Bibliometric analysis

Following the SLR, a Bibliometric Analysis comprehensively examine big BIM data in AEC sector. By employing clustering analysis and keyword co-occurrence, the research landscape is mapped out. A total of 125 records were exported from Endnote20 to VOSviewer, a tool that facilitates data generation, visualisation, and bibliometric analysis. This method, chosen for its objectivity, analyses existing literature based solely on reported data, thus minimising potential author bias [84,107].

VOSviewer was used for text mining to extract keywords from titles, abstracts, and citation contexts [105]. The tool generates a co-occurrence network of keywords, visualised on a two-dimensional map, where the distance between keywords reflects their co-occurrence similarity. The clustering function groups keywords based on these patterns [106,109,110].

The findings from this bibliometric analysis provide a solid foundation for developing hypotheses based on observed trends in the literature, which can be validated in future studies [84]. Abstracts and keywords are analysed to create clusters that highlight the most significant components of the research area, offering a comprehensive review of big BIM data literature.

4. Literature analysis

4.1.1. Systematic review: Preliminary findings and analysis

Over an 11-year period, research in this field has shown significant growth in both volume and scope. Journal articles comprised the majority with 76 records, followed by conference proceedings with 41 records. Conference papers and serial publications accounted for 4 and 3 records respectively, while a single book represented 1 record. Fig. 4, a time series graph, illustrates this growth with the X-axis indicating publication year and the Y-axis showing publication count. The bar graph displays yearly publication numbers, while the grey line depicts cumulative totals. Despite the impressive growth and trend in publication numbers, the qualitative aspects of these studies are noteworthy. Many of the publications are either conceptual or exploratory, involving small-scale experiments or being at initial testing stages. This indicates that while the research output is increasing, much of it is still in the formative stages, laying the groundwork for more extensive and practical applications in the future.

The variation in publication trends over the search period can be

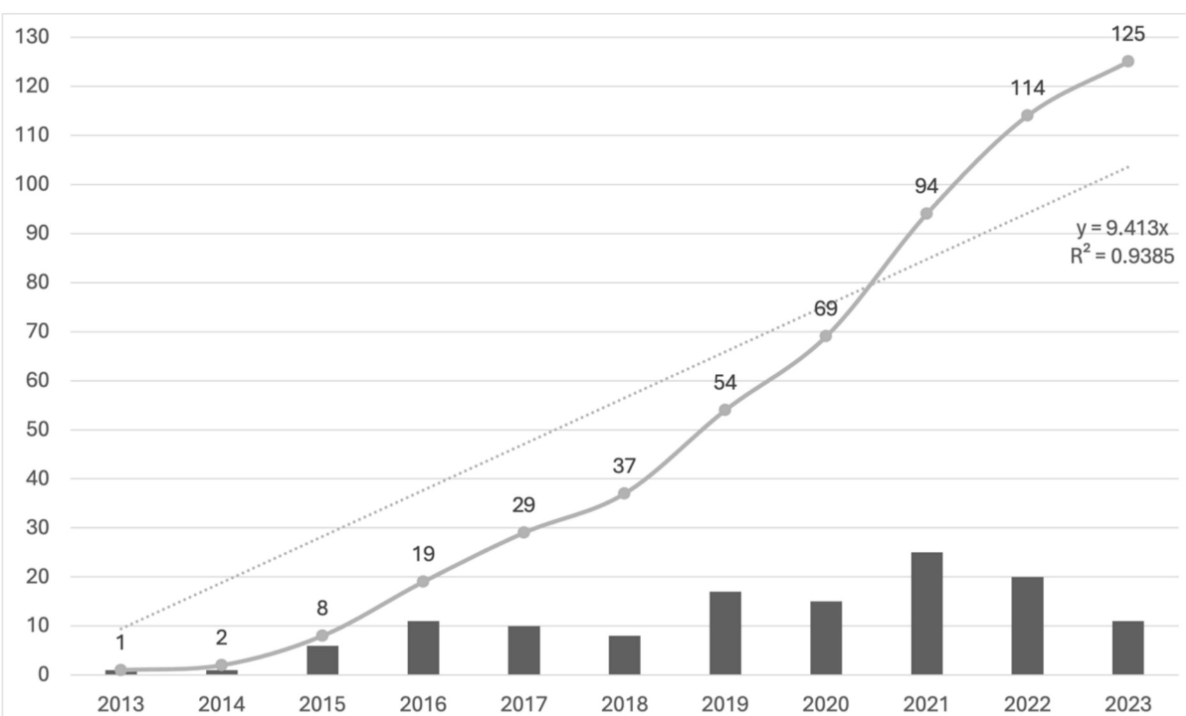

Fig. 4. Annual publication trend of the field.

attributed to several key factors. During the early years (2013–2015), growth was slow due to limited awareness and adoption of integrating BIM with big data. The AEC industry was still becoming familiar with the benefits of BIM, and technical challenges such as data interoperability were prevalent [5,35,101]. From 2016 to 2019, there was moderate growth as recognition of BIM's benefits increased, leading to greater interest in its integration with big data. Researchers began to focus on practical applications and overcoming initial technical barriers. The sharp increase in publications post-2020 indicates a significant rise in academic and industry interest due to the maturity of BIM and big data technologies, alongside advancements in related technical fields such as sensor networks, cloud computing, and advanced analytical models requiring extensive data for accurate results, such as machine learning (ML) and Artificial Intelligence (AI) [7,8,16,28,128]. This reflects broader adoption and more sophisticated research in this integration, aligning with the trends observed in the cumulative publication totals.

4.1.2. *Bibliometric analysis: Keyword co-occurrence*

The purpose of this analysis is to provide a holistic overview of BIM and big data integration in AEC sector. From the initial pool of 1018 extracted keywords, 139 occurred two or more times, indicating their prominence in the literature. After applying inclusion criteria, 135 keywords were selected to build the map, signifying the breadth and depth of the research domain.

The subsequent identification of 10 clusters within the keyword co-occurrence map provides valuable insights into the interconnected themes and focal points of research in the field of big BIM data. These clusters represent significant areas of interest and highlight the multifaceted nature of the domain. Notable clusters including "big data," "architectural design," "BIM," and "information management" underscore foundational concepts and technologies central to the integration of BIM and big data. Clusters such as "construction industry," "project management," and "lifecycle" emphasise practical applications and operational aspects within the AEC sector. These clusters elucidate the role of big BIM data in enhancing project delivery, optimising resource allocation, and improving overall lifecycle management practices. Moreover, clusters such as "information theory," "digital storage," and "data visualisation" shed light on the underlying principles and technical aspects of managing and analysing large volumes of data within the context of BIM. These clusters highlight the importance of information theory, data storage solutions, and advanced visualisation techniques in harnessing the potential of big BIM data.

Fig. 5 outlines the diverse subdomains of BIM and big data integration within AEC organisations, highlighting their applications and potential. It identifies technologies like cloud computing, robotics, IoT, risk analysis, blockchain, and digital twins, underscoring their relevance to smart buildings, smart cities, facility management, and asset management. Insights from keyword co-occurrence analysis are enriched through contextualisation via the SAM in subsequent sections. This approach illuminates how these thematic clusters align with AEC organisational objectives and IT capabilities, offering deeper insights into the practical integration of big BIM data.

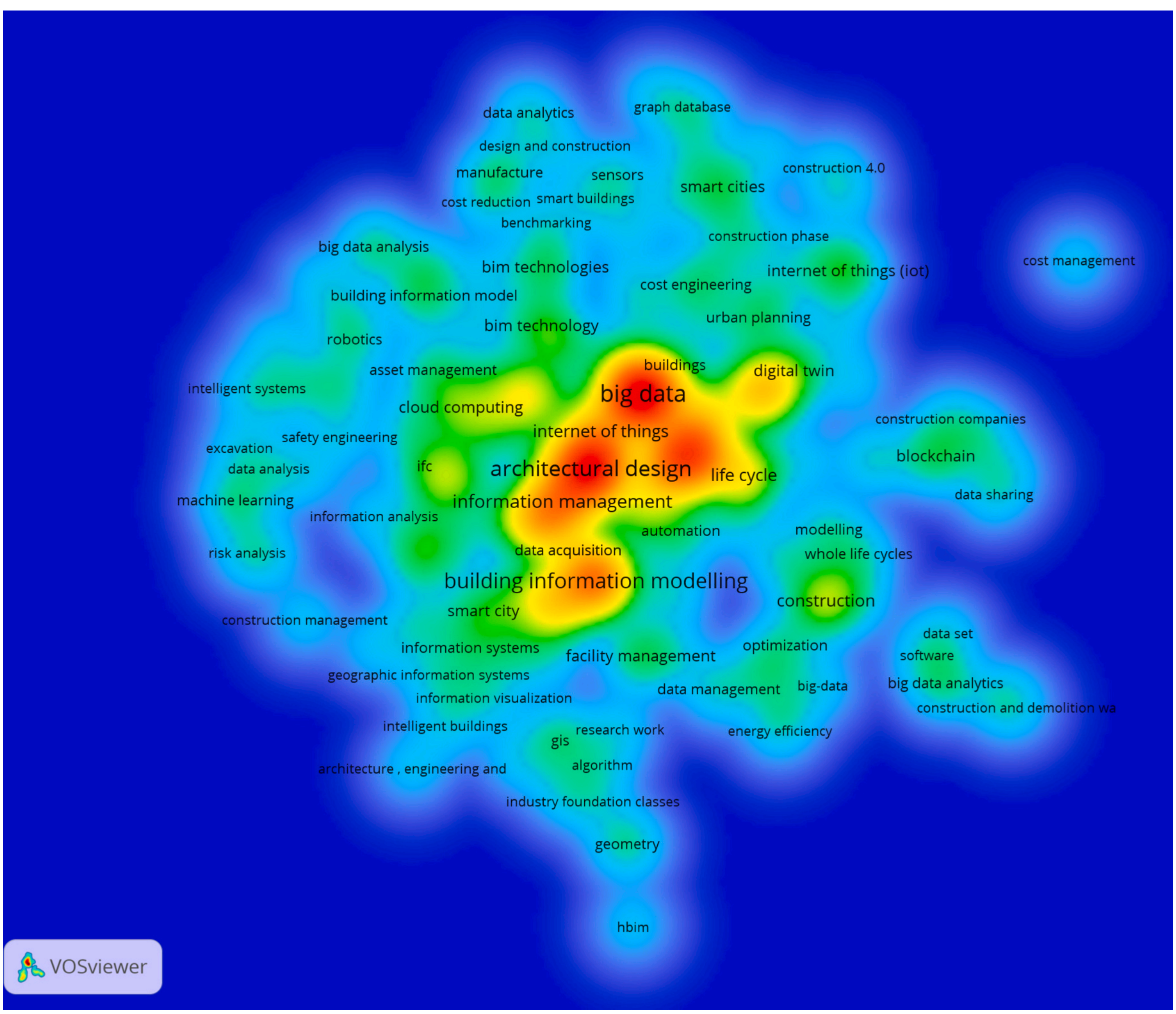

Fig. 5. Network visualisation map of most related topics in big BIM data.

4.1.3. Literature classification and analysis

The results from the SLR and BA can be effectively contextualised and analysed using the Strategic Alignment Model (SAM) proposed by Henderson and Venkatraman [45]. This model comprises four domains:

1) AEC organisational infrastructure and processes,
2) Big BIM data (IT) infrastructure and processes,
3) AEC organisational strategic analysis & framework, and
4) Big BIM data (IT) strategic analysis & framework.

The adoption of this framework was intentional, given its alignment with the principles of the Data Management Body of Knowledge [32], which delineates the knowledge and business management areas of data management. Within this framework, data governance holds a pivotal position, ensuring coherence and equilibrium across various organisational functions. This is particularly pertinent to the study's focus on big BIM data, emphasising the critical necessity for strategic alignment between organisational levels and the management of big BIM data, representing the information technology (IT) component. A summary of the SLR aligned with the SAM is depicted in Fig. 6.

Analysing the keyword co-occurrence analysis results within the framework of SAM reveals several significant insights. Clusters related to "lifecycle" and "project management" intersect with the organisational infrastructure and processes domain of SAM. These clusters highlight the organisational capabilities and processes required to effectively manage, store, and utilise big BIM data through a sophisticated project and organisational administrative structure, processes and AEC specific skill sets. From establishing robust organisational workflow to implementing efficient project management practices by training their staffs, organisations must align their internal structures and processes with the demands of big BIM data integration.

Similarly, clusters associated with "digital storage," and "data visualisation" align with the information technology infrastructure and processes domain of SAM. These clusters emphasise the importance of building resilient IT infrastructures capable of supporting the storage, processing, and visualisation of large-scale BIM datasets throughout the project lifecycle. By investing in robust IT infrastructure and embracing emerging technologies, organisations can enhance the scalability, reliability, and security of their big BIM data environments.

Furthermore, clusters like "architectural design," and "construction industry" resonate with the AEC business strategy domain of SAM. These clusters underscore the strategic imperative of integrating big BIM data into key business scope and distinctive competency and business governance. By harnessing big BIM data, organisations can enhance their competitive positioning, improve project outcomes, and drive innovation across the project lifecycle.

Finally, clusters such as "big data" and "BIM" exhibit relevance across multiple domains within the SAM framework, reflecting their pervasive influence throughout the strategic and technical landscape. Additionally, keywords like "information management" and "information theory" closely align with the Big BIM data (IT) strategy domain of SAM, highlighting the technological underpinnings of big BIM data. These clusters underscore the strategic imperative of leveraging advanced data analytics, information management systems, and big BIM data governance to extract actionable insights from BIM-enabled datasets.

5. Results and discussion

5.1. AEC organisational infrastructure and processes domain

The 24 records mapped to the AEC organisational infrastructure and processes domain highlight the strategic value that Big BIM Data brings to business management across various construction phases. Although some benefits span multiple phases, these studies commonly adopt a small-scale approach, focusing on individual construction projects and specific aspects of the project lifecycle. While benefits often span multiple stages, the studies predominantly focus on individual projects and specific lifecycle aspects. Notably, post-construction stages receive significant attention, with 34 studies highlighting the maturity of technologies like sensor networks and IoT for implementation during this phase, see Fig. 7. In contrast, pre-construction and construction stages are less emphasised, with 14 and 20 studies respectively. These challenges may arise from the constraints imposed by active construction conditions, hindering the deployment of sensor networks and IoT devices on-site and resulting in data unavailability. The strategic benefits of Big BIM Data in business management are detailed across three distinct sections focusing on the pre-construction, construction, and post-construction phases.

5.1.1. Pre-construction

The analysis of 14 records underscores the strategic benefits that big BIM data brings to the business management domain of AEC organisations, see Table 5. Key trends include leveraging data-driven insights during the pre-construction stage to enhance sustainable building design, streamline offsite construction processes, and facilitate digital

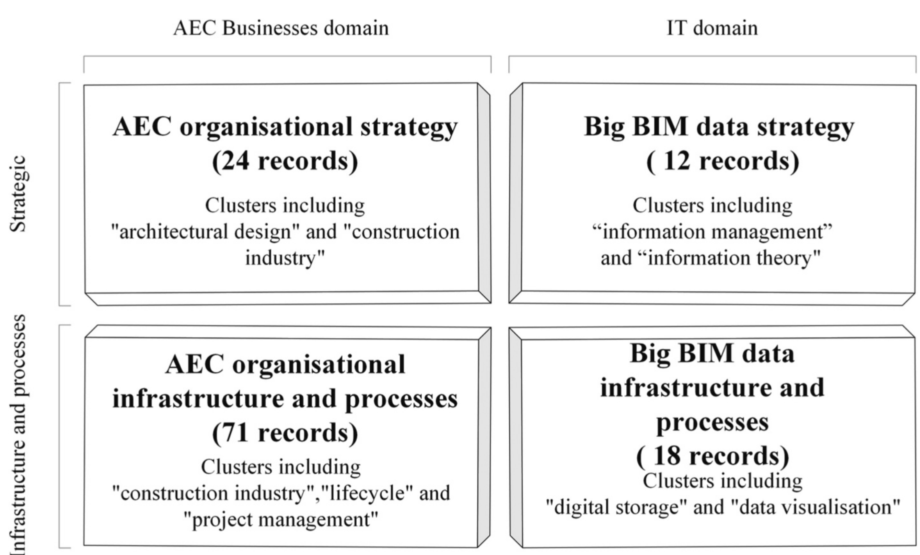

Fig. 6. SLR and BA finding mapped according to the SAM domains.

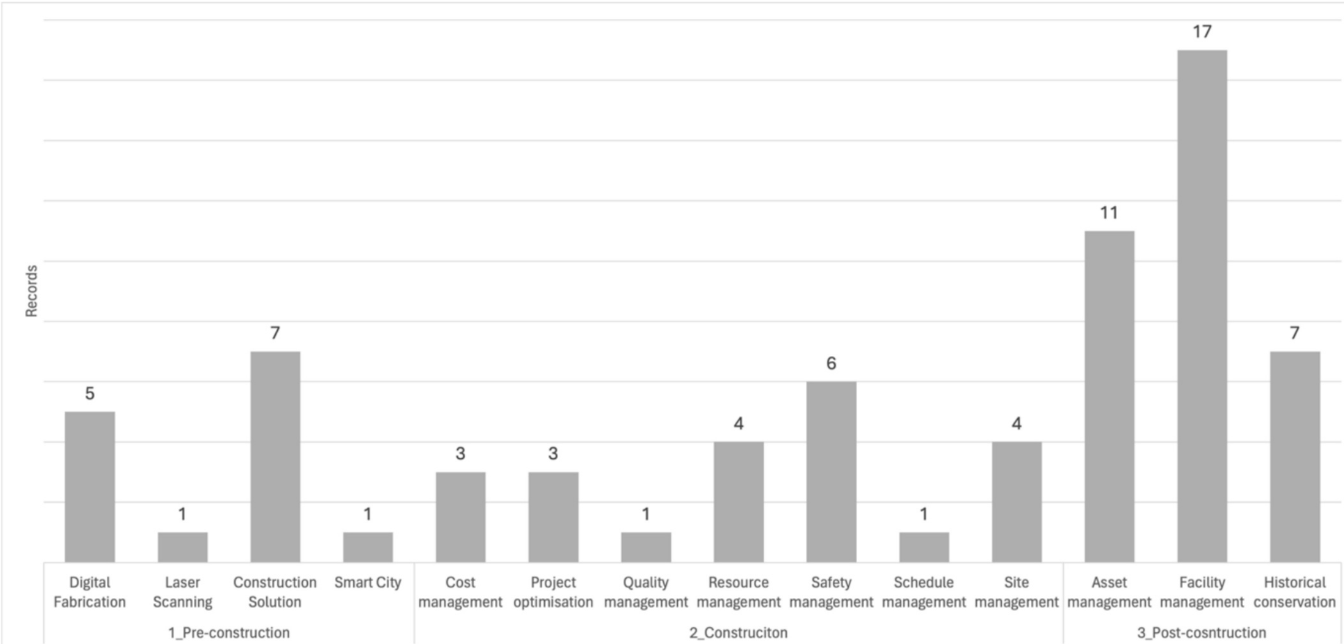

Fig. 7. Summary of AEC organisational infrastructure and processes research domain.

fabrication. Additionally, Big BIM Data improves the accuracy of as-built modeling, enables the exploration of construction alternatives, and supports the development and management of smart cities.

Notable studies include Gbadamosi et al. [37], who introduce BIG-DOR, integrating BIM and big data for offsite construction, and He et al. [44], focusing on BIM applications for 3D printing and modular housing. Chen et al. [25]; Chen et al. [26] highlight modular integrated construction for emergency hospitals, while Jalilzadehazhari et al. [56] combine BIM with design experiments and AHP for energy-efficient design. Fan and Shi [36] enhance digital construction by integrating BIM with 3D laser scanning for accurate modeling. Redmond et al. [88] evaluate green building technologies using big data and BIM, while Joyce et al. [61] and Li et al. [68] emphasise decision-making in design and cost-effective construction purchasing. Kagan [62] and Zeng [124] propose systems for estimating project costs and optimising civil engineering cost management. Rogalska and Hejducki [91] integrate worker absenteeism into BIM methodologies, and Shahi et al. [96] assess e-permitting practices' impact on projects. Finally, Lv et al. [73] explore using BIM big data for Smart City digital twins to enhance urban planning, infrastructure management, and emergency response, introducing an efficient data fusion algorithm.

5.1.2. Construction

The 22 records identified in the construction phase primarily focused on enhancing various aspects of construction project management. These studies concentrate on optimising seven critical areas: cost management, quality management, resource management, safety management, schedule management, site management, and overall project optimisation. Table 6 presents a comprehensive summary of the findings, highlighting key insights and recommendations from each study.

The records reviewed emphasise several strategic value towards construction project management. Cost management strategies focus on improving cost estimation accuracy, reducing project management expenses, and enhancing overall project value through standardised protocols and integrated approaches [49,72,114]. Project performance is improved through integrating daily reports into 5D BIM models and emphasising big data for safety management [75,77]. Quality assurance benefits from using RNN-LSTM networks to predict and mitigate construction issues [111]. Resource management focuses on optimising allocation and minimising waste, supported by frameworks for prediction and mitigation [15,17]. Safety management is enhanced by dynamic hazard identification and real-time monitoring [22,102]. Schedule management efficiency and data sharing are significantly improved with BIM-based project supervision systems [57]. Lastly, sustainable site management is achieved through visual data and detection algorithms, with prefabricated buildings reducing resource waste and energy consumption [104,119].

5.1.3. Post-construction

The strategic value that big BIM data brings to this post-construction phase, listed in Table 7, through three primary areas: facility management, asset management, and preservation, often termed as Historic Building Information Modeling (HBIM). This not only emphasise efficient asset operation but also prioritise long-term preservation efforts.

Facility management focuses on overseeing and enhancing an organisation's physical assets, with several studies illustrating advancements in this field. Notably, Agostinelli and Cumo [1] developed a predictive maintenance strategy integrating statistical data with labour costs and maintenance durations, significantly improving residential system operations through Big Data analysis in BIM-based projects. Arslan et al. [7,8] combined BIM software with wireless sensor technology to create a proactive safety management system, enabling informed decision-making via data visualisations. Ioannidis et al. [53] assessed building performance, emphasising occupancy impacts on metrics like lighting and HVAC usage and tested their tool on real building data to assist managers with energy and occupancy insights.

In asset management, Zhu et al. [129] explored the strategic balancing of costs, risks, and opportunities using Integrated Workplace Management Systems (IWMS). Aligning BIM with IWMS enhances asset lifecycle management, bringing operational improvements such as streamlined processes, cost reduction, and increased productivity [51]. Howell et al. [47] proposed merging systems like smart homes and geographic information systems through semantic web technology and IoT, promoting enhanced system performance.

Historical conservation within asset management has seen significant attention, particularly through HBIM and big data. Notably, Arnold and Lafreniere [6] used Esri's CityEngine to model a post-industrial landscape's heritage, providing valuable insights for managing

Table 5
Practical application of big BIM data during the pre-construction phase.

Application	ID	Description
Digital Fabrication of Industrialized Buildings (5 Records)	77	Big data for Design Options Repository: Towards a DFMA approach for offsite construction
	80	BIM-enabled computerized design and digital fabrication of industrialized buildings: A case study
	91	Modular Structure Construction Progress Scenario: A Case Study of an Emergency Hospital to Address the COVID-19 Pandemic
	92	Modular composite building in urgent emergency engineering projects: A case study of accelerated design and construction of Wuhan Thunder God Mountain/Leishenshan hospital to COVID-19 pandemic
	100	Achieving a trade-off construction solution using BIM, an optimization algorithm, and a multi-criteria decision-making method
Integration of 3D Laser Scanning with BIM (1 record)	82	BIM combined with the 3D laser scanning technology to lead the changes of the design industry in the future
Achieving a Trade-Off Construction Solution Using BIM (7 Records)	29	Stream technologies of data analysis in organisational and technological design in construction
	31	An application on building information model to procurement strategy of copper raw material with big data analytics
	49	Employing an exploratory research stage to evaluate green building technologies for sustainable systems
	86	Research on Integrated Management Mode of Civil Engineering Cost Based on BIM Technology
	102	Seeing numbers: Considering the effect of presentation of engineering data in design
	115	The possible impact of employee absenteeism risk on a construction project
	117	Framework for Automated Model-Based e-Permitting System for Municipal Jurisdictions
Smart City Construction and Management by Digital Twins and BIM (1 record)	109	Smart city construction and management by digital twins and BIM big data in COVID-19 scenario

historical assets. [66] employed digital photogrammetry and thermographic cameras to survey historical façades, using orthophotos and mosaics for rapid documentation and preventive maintenance. Nagy and Ashraf [81] introduced a framework for monitoring heritage buildings' energy performance with smart sensing and digital platforms, enabling real-time monitoring and data management. These studies collectively demonstrate the potential of big data and BIM technologies in enhancing facility and asset management, as well as historical conservation.

5.2. *Big BIM data (IT) infrastructure and processes domain*

The research on IT infrastructure and processes enhances the strategic value aligned with the AEC organisational infrastructure and processes domain discussed earlier. In contrast to AEC organisational infrastructure and processes research, this domain focuses primarily on the technical prerequisites crucial for the effective implementation and delivery of value from big BIM data. It also provides a comprehensive platform for collecting, integrating, storing, analysing, and visualizing big BIM data throughout the project lifecycle. This section thus analyses the influence of the technical information technology domain within AEC organisations.

Table 6
Practical application of big BIM data during the construction phase.

Application	ID	Description
Cost management (3 records)	24	Application of BIM Big Data in Construction Engineering Cost
	35	BIM and Big Data for Construction Cost Management
	62	BIM Based Project Investment Cost Control Strategy in Big Data Environment
Project performance optimisation (3 records)	38	Analysing project data in BIM with descriptive analytics to improve project performance
	39	Information Management Strategy of Bridge Construction Technology Based on Big Data
	121	Digital transformation to improve quality, efficiency and safety in construction of roads incorporating recycled materials
Quality Management (1 record)	60	Research on optimization of big data construction engineering quality management based on RnN-LSTM
Resource management (4 records)	08	Big data architecture for construction waste analytics (CWA): A conceptual framework
	09	Analysis of critical features and evaluation of BIM software: towards a plug-in for construction waste minimization using big data
	114	Review of construction and demolition waste management tools and frameworks with the classification, causes, and impacts of the waste
	116	Building Information Modeling for Application in Geotechnical Engineering
Safety management (6 records)	14	Uncertainty and Sensitivity Analysis of Significant Parameters for Superlarge Diameter Shield Excavation
	18	Construction safety monitoring and control of urban rail transit based on BIM
	55	Application of Intelligent Safety Supervision Based on Artificial Intelligence Technology
	63	Safety monitoring platform for deep excavation based on BIM and big data technology
	107	Risk assessment and management of excavation system based on fuzzy set theory and machine learning methods
	108	BIM-based digital platform and risk management system for mountain tunnel construction
Schedule management (1 record)	27	Implementation of Construction Project Supervision System Based on BIM
Site management (4 records)	58	Sustainable management of construction site big visual data
	66	The Construction Site Management of Concrete Prefabricated Buildings by ISM-ANP Network Structure Model and BIM under Big Data Text Mining
	94	Integration of Building Information Modeling and Artificial Intelligence Systems to Create a Digital Twin of the Construction Site
	98	Examining the quality and management of non-geometric building information modeling data at project hand-over

The adoption of big data requires a significant changes and impact the existing technical information technology domain. In a comparative analysis of big data platforms, five major frameworks were assessed against existing systematic reviews [41,52]. Apache Hadoop emerged as the most prominent platform, supported by multiple records [7–9,15,23,24,118], followed by Apache Spark [15,87] and Flink [83], demonstrating sustained popularity in technical research. However, due to rapid advancements in big data technology and the prevalence of cloud services encompassing storage, processing, and analytics, several other platforms received limited attention in these studies.

Both quantitative and qualitative analyses underscore the necessity for additional technological support when integrating BIM and big data. This support primarily revolves around three key technologies: databases, cloud computing, and blockchain, as outlined in Table 8. However, further investigation reveals that these technologies also depend on integration with secondary supporting technologies such as IoT,

Table 7
Practical application of big BIM data during the post-construction phase.

Application	ID	Description
Facilities Management (17 records)	01	Machine learning approach for predictive maintenance in an advanced building management system
	05	Building Information Modeling (BIM) Enabled Facilities management using Hadoop architecture
	10	Improved visualisation of infrastructure monitoring data using building information modeling
	21	The conditions data model supporting building information models in facility management
	26	Occupancy driven building performance assessment
	40	Spoken dialogue BIM systems – an application of big data in construction
	43	Exploiting internet of things and building information modeling framework for management of cognitive buildings
	44	Digital Twin Hospital Buildings: An Exemplary Case Study through Continuous Lifecycle Integration
	48	Leveraging Existing Sensor Networks as IoT Devices for Smart Buildings
	56	Tracking Changes in Buildings over Time Fully Automated Reconstruction and Difference Detection of 3d Scan and BIM files
	67	Research on Building Space Model Method Based on Big Data Map Visual Design
	76	BIM-based big data analytic system for healthcare facility management
	96	Lean management framework for healthcare facilities integrating BIM, BEPS and big data analytics
	97	Refurbishment and school buildings management in a smart building environment
	105	Intelligent Monitoring Platform and Application for Building Energy Using Information Based on Digital Twin
	111	Use of BIM-FM to transform large conventional public buildings into efficient and smart sustainable buildings
	112	Framework for Heterogeneous Sensor Data Stream Management with BIM and WSN
Asset Management (11 records)	06	Leveraging BIM and Big Data to deliver well maintained highways
	17	Investigation of Coal Preparation for Life Cycle by Using Building Information Modeling (BIM): A Case Study
	22	Putting asset data at the heart of organisational decision-making using an Integrated Workplace Management System
	23	Integrating building and urban semantics to empower smart water solutions
	28	Research and Design of Infrastructure Monitoring Platform of Intelligent High Speed Railway
	51	Traffic Planning as a Preliminary Tool in Project Documentation for BIM
	53	A BIM and machine learning integration framework for automated property valuation
	57	Semantic enrichment for rooftop modeling using aerial LiDAR reflectance
	74	BIM/GIS integration for web GIS-based bridge management
	78	Knowledge driven approach for smart bridge maintenance using big data mining
	120	A digital twin smart city for citizen feedback
Historical conservation (7 records)	04	Creating a longitudinal, data-driven 3D model of change over time in a post-industrial landscape using GIS and CityEngine
	07	BIM orientation: Grades of generation and information for different type of analysis and management process
	13	SCAN-TO-BIM vs 3D IDEAL MODEL HBIM: PARAMETRIC TOOLS to STUDY DOMES GEOMETRY
	30	VPL for HBIM: Algorithmic Generative Processes for the Thematic Mapping of Information Models
	37	Improved Interaction of BIM Models for Historic Buildings with a Game Engine Platform
	42	HBIM platform & smart sensing as a tool for monitoring and visualizing energy performance of heritage buildings
	72	Integration application system of Chinese wooden architecture heritages based on BIM

Table 8
Technological scope supporting Big BIM data platform.

Technology	ID	Description
Database technology (6 records)	19	IFC and Monitoring Database System Based on Graph Data Models
	34	BIM model components retrieval method based on visual attention
	65	Research on Big Data Compression Algorithm Based on BIM
	70	BIM-CityGML data integration for modern urban challenges
	75	A cloud-based system framework for performing online viewing, storage, and analysis on big data of massive BIMs
	79	Parallel computing-based online geometry triangulation for building information modeling utilising big data
Cloud technology (7 records)	15	A cloud-based system framework for storage and analysis on big data of massive BIMs
	16	A cloud-based framework for online management of massive BIMs using Hadoop and WebGL
	32	A Natural-Language-Based Approach to Intelligent Data Retrieval and Representation for Cloud BIM
	36	BIM Big Data Storage in WebVRGIS
	50	Understanding quality of analytics trade-offs in an end-to-end machine learning-based classification system for building information modeling
	52	A simplified bim model server on a big data platform
	87	A collaborative unified computing platform for building information modeling (BIM)
Blockchain technology (5 records)	20	CPAS: A Copyright-Protected Autonomous Sharing Scheme by Blockchain and Smart Contract for BIM Data
	46	Towards effective project documentation, transparency, and data-driven decision-making through bim-blockchain based applications
	61	A Blockchain-based and Privacy-Protected Method for Sharing of BIM Big Data
	73	BcBIM: A Blockchain-Based Big Data Model for BIM Modification Audit and Provenance in Mobile Cloud
	89	Information traceability platforms for asset data lifecycle: blockchain-based technologies

sensor networks, ML and AI. The impact of these technologies on the technical information technology domain within AEC organisations is detailed across three distinct sections focusing on database technology, cloud technology, and blockchain technology.

5.2.1. Database technology

The research in database technology focuses on optimising the retrieval of BIM components using user attention, developing a framework for storing BIM big data, and implementing strategies for integrating BIM with CityGML data. These efforts aim to improve data retrieval efficiency and promote interoperability in the field of building information modeling. Gradišar and Dolenc [38] integrate monitoring data into building information models via graph data management systems and the IFC standard, providing scalability and collaboration for smart cities and big data challenges. [71] propose a method for BIM component retrieval based on user visual attention, enabling efficient access to component information at different stages of building model applications. [118] introduces a BIM big data storage framework using the IFC standard and an improved compression algorithm, enhancing efficiency for larger datasets and suggesting an Elasticsearch Hadoop server cluster for swift data querying. [123] present BIM-CityGML Data Integration (BCDI), allowing real-time queries for geometric and non-geometric data, uniquely addressing data mapping between ifcXML and CityGML standards.

5.2.2. Cloud technology

Chen and Chang [23] introduced a system utilising Cloud technology to establish a data centre for managing multiple BIMs concurrently. This BIM data centre not only handles massive BIM data using distributed servers but also facilitates access from various online devices for information sharing and visualisation. The study extended BIM to dynamic BIM, incorporating dynamic data such as historical records from facility monitoring and user experience parameters. This extension transformed dynamic BIM into a parametric model capable of simulating user behaviours. The study proposes a Cloud-based system framework for effectively retrieving information for various applications through big data analysis based on parallel processing of large datasets.

Chen et al. [24] proposed a cloud-based system framework utilising Bigtable and MapReduce for scalable storage and processing of large BIMs. Their results demonstrated the feasibility of managing massive BIMs reliably using this framework. Lin et al. [69] suggested a strategy incorporating natural language processing to improve data retrieval in cloud-based BIM applications, enhancing user interaction and data representation. Their case study showcased the automatic retrieval and aggregation of user-concerned data based on cloud resources, leading to enhanced user benefits and BIM value. Lv et al. [74] introduced a hybrid storage solution for BIM big data within a WebVRGIS, revolutionising city information management and diversely storing geospatial data. Ryu et al. [92] emphasised the integration of ML techniques across BIM phases for BIM classification system design. Solihin and Eastman [98] proposed a simplified schema, BIMRL, tailored for efficient utilisation in big data platforms, demonstrated through a proof-of-concept using OrientDB for transforming relational database BIMRL data. These studies collectively illustrate the evolving landscape of cloud-based approaches in BIM management and processing.

5.2.3. Blockchain technology

Sharing BIM data among contributors is crucial but challenging due to intellectual property concerns. Blockchain and smart contracts are commonly employed to enable data reuse while protecting intellectual property. Guo et al. [40] proposed a blockchain framework with smart contracts for safeguarding BIM data copyrights. Their autonomous scheme ensures copyright confirmation, authentication, and verification in open data sharing, validated through practical experiments. Raco et al. [85] developed an integration solution that uses blockchain within the BIM platform, facilitating certification processes, managing transitions between professionals, and handling collaborative contracts and work progress through Smart Contracts in public procurement scenarios. Wang et al. [112] proposed a uniform blockchain framework for smart construction, emphasising the selective encryption of critical BIM data and implementing copyright protection and signature mechanisms. This approach offers confidentiality, encourages participation, and bridges multiple information security management domains for large-scale sharing. Zheng et al. [128] introduced the BcBIM model, highlighting its potential to guide architecture design and integrate BIM cloud services for efficient big data sharing. The model organises BIM data using blockchains, ensuring traceability, authentication, prevention of tampering, and support for open sharing, data audit, and provenance.

5.3. AEC Organisational strategy domain

The research within the AEC Organisational Strategy domain, detailed in Table 9, shares a common objective: to provide a comprehensive overview of AEC organisations by delivering strategic value through two primary areas—business scope & distinctive competencies, and organisational governance factors. These studies diverge from focusing solely on individual construction projects and specific project lifecycle aspects. Instead, they aim to establish overarching strategic frameworks, conceptual models, and systematic reviews that offer guidance, new technological insights, insights into AEC market trends, and validate the value proposition of integrating big data, BIM, or a combination thereof within AEC organisations. Due to their broad scope, these studies are challenging to categorise into the specific sub-domains outlined in the SAM and are therefore discussed collectively.

Table 9
Big BIM data Strategic analysis and Conceptual framework studies.

Field	ID	Description
Organisational Strategic analysis & framework (24 records)	2	Modeling dependency networks to inform data structures in BIM and smart cities
	3	Correlation between BIM data creation and big data attributes in construction
	11	Challenges of Big Data in the age of Building Information Modeling: A high-level conceptual pipeline
	41	Spatial Typology for BIM Preassembling for Synthetic Architectural Design
	47	Adoption of Big Data analytics in construction: development of a conceptual model
	59	Research on Collaborative Mechanism of design and construction based on BIM technology and application of typical cases
	64	Study on construction engineering management based on BIM from the perspective of big data
	71	Digital Twin for Accelerating Sustainability in Positive Energy District: A Review of Simulation Tools and Applications
	81	Visualisation analysis of cross research between big data and construction industry based on knowledge graph
	84	Evaluation of Complexity Issues in Building Information Modeling Diffusion Research
	88	New perspectives for bim usage in transportation infrastructure projects
	90	Construction of Integrated Evaluation System for Green Port Construction Based on BIM Technology
	93	Exploring Building Information Modeling (BIM) and Internet of Things (IoT) Integration for Sustainable Building
	99	The adoption of IoT in the Malaysian construction industry: Towards construction 4.0
	101	Science mapping approach to assisting the review of construction and demolition waste management research published between 2009 and 2018
	103	Constructability: Outline of Past, Present, and Future Research
	104	Making an engine: performativities of building information standards
	106	Review of building energy performance certification schemes towards future improvement
	118	An assessment on the parallel impacts of building information modeling and big data on project operation and maintenance
	119	Research on the Realisation Path of Railway Intelligent Construction Based on System Engineering
	122	Application Research of BIM Technology in Bridge Reconstruction and Extension Engineering
	123	Imperative role of technology intervention and implementation for automation in the construction industry
	127	Research on the Relationship between Construction 4.0 and Construction Firm's Performance: Based on the Mediating Role of Technological Innovation Capability
	130	A critical review and comparative analysis of cost management on prefabricated construction research (2000–2022)

5.3.1. Business scope and distinctive competency

Numerous studies explore the integration of BIM with big data, emphasising BIM's role as a cornerstone of digital strategy [4]. This integration enables the creation of extensive digital datasets that drive advancements in construction project management, sustainability, and efficiency. Applications span diverse sectors such as transportation infrastructure, green port construction [21], bridge reconstruction [125], railway intelligent construction [115], and deep excavation projects [116], showcasing sector-specific implementations. In transportation infrastructure, BIM and big data enhance efficiency across phases from planning to maintenance [70,76,117]. Railway intelligent construction exemplifies transformative practices by integrating geospatial data, track monitoring, and passenger flow information to optimise planning, monitoring, and maintenance processes, improving safety and operational efficiency. Similarly, in sustainable building construction, BIM and big data optimise design, construction, and operation to meet sustainability goals, emphasising energy efficiency and occupant well-being [13,21,27,60,86,127].

5.3.2. AEC business governance

The adoption of big data analytics in construction, particularly for project operation, maintenance, and performance evaluation, is highlighted in recent studies [97], aligning with AEC organisational infrastructure and processes. Big BIM data analytics present opportunities to optimise project operation and maintenance by analysing sensor data, BIM models, and other sources. These insights enable construction companies to enhance decision-making and efficiency in project management and maintenance activities.

In sustainable development contexts like green port construction, BIM and big data play pivotal roles [21]. Evaluative models, such as those proposed by Cao et al. [21], facilitate structured assessments of sustainability and efficiency outcomes in AEC projects. By leveraging BIM construction information and big data analytics, organisations can align project planning, design, and execution with sustainability goals and operational efficiency targets. This approach optimises resource allocation, risk mitigation, and overall project outcomes, enhancing AEC business governance through evidence-based decision-making and sustainable practices.

Additionally, Jin et al. [60] emphasises the importance of benchmarking construction and demolition (C&D) waste throughout project stages. They advocate for standardised criteria and frameworks to accurately measure C&D waste generation and management effectiveness. Such metrics, including economic performance and environmental impact indicators, provide a comprehensive assessment of C&D waste management practices. This holistic approach supports the development of sustainable waste management strategies within the construction industry [29,42,82].

5.4. Big BIM data (IT) strategy domain

The final category, Big BIM data strategy domain, focuses on providing strategic frameworks for the adoption of big BIM data information technology infrastructure and processes within the AEC organisation. It specifically addresses the technological scope of big BIM data, systematic competencies, and strategic IT governance related to big BIM data within the AEC organisation. Similar to AEC Organisational Strategic strategy domain, the primary focus of these records is to offer strategic frameworks, conceptual models, and systematic reviews of current research trends, progress, and future directions (Table 10).

5.4.1. Scope of big BIM data

Several studies in this category focus on designing system architectures and conceptual frameworks to effectively manage BIM big data. These frameworks aim to integrate BIM data with other technologies such as GIS and big data analytics to optimise asset management [51], emergency response systems [122], and construction project collaboration [30,76]. The architectures typically involve scalable, distributed systems capable of efficiently storing, processing, and analysing vast amounts of BIM data. Cloud computing and distributed storage technologies play crucial roles in ensuring effective access and utilisation of BIM data across different phases of the construction lifecycle.

Table 10
Big BIM data infrastructures and processes.

Field	ID	Description
Big BIM data (IT) strategy (12 records)	12	Geospatial data management research: Progress and future directions
	25	BIM big data system architecture for asset management: a conceptual framework
	33	System Architecture and Key Technologies for the Whole Life Cycle of Smart Road
	45	Research directions on GIS database design and management
	68	Research and Application of BIM Engineering Management Platform Combining Big Data
	69	Design of assembled emergency medical system based on BIM+
	85	BIM cloud score: Benchmarking BIM performance
	95	Lean based maturity framework integrating value, BIM and big data analytics: Evidence from AEC industry
	110	Achieving a trade-off construction solution using BIM, an optimization algorithm, and a multi-criteria decision-making method
	125	Digital Technology in Architecture, Engineering, and Construction (AEC) Industry: Research Trends and Practical Status towards Construction 4.0
	126	Integration of Building Information Modeling (BIM) and Big Data in China: Recent Application and Future Perspective
	128	Research on Integration of Digital Graphic and Information in Building Information Modeling

5.4.2. Systematic competencies

Furthermore, there is significant emphasis on developing metrics and methodologies for measuring and enhancing the performance of Big BIM Data initiatives within IT frameworks. This includes establishing key performance indicators (KPIs), benchmarking BIM data processes, and implementing continuous improvement strategies [18,30,33,76]. These methodologies aim to set standardised metrics and criteria for evaluating the effectiveness and efficiency of BIM strategies and performance in construction projects. By defining benchmarks, stakeholders can assess their BIM practices against industry standards, identify areas for enhancement, and draw insights from successful BIM implementations.

5.4.3. Strategic IT governance

Strategic IT governance focuses on leveraging IT frameworks to optimise Big BIM Data initiatives. It involves implementing governance structures and frameworks that support the integration of BIM data with GIS and big data analytics for enhanced decision-making and operational efficiency in construction projects. Establishing effective IT governance ensures that BIM data management and analysis capabilities are aligned with strategic objectives, enabling stakeholders to drive innovation, manage risks, and achieve sustainable growth in construction practices [113,117,121].

6. Research gap and future research direction

6.1. A strategic alignment models: Review and analysis

6.1.1. Business – Big BIM data AEC organisational infrastructure and processes gap

The focus of AEC organisational infrastructure and processes research lies in delivering tangible value. However, the limitation of small-scale experiments, conducted project by project identified in the existing systematic review, hampers these studies from considering the broader organisational perspective and the potential value they could bring beyond individual projects see Fig. 8.

Moreover, the scarcity of studies focused on pre-construction stages highlights a research gap in the alignment of big BIM data during the initial project lifecycle phases. This gap may arise from perceived

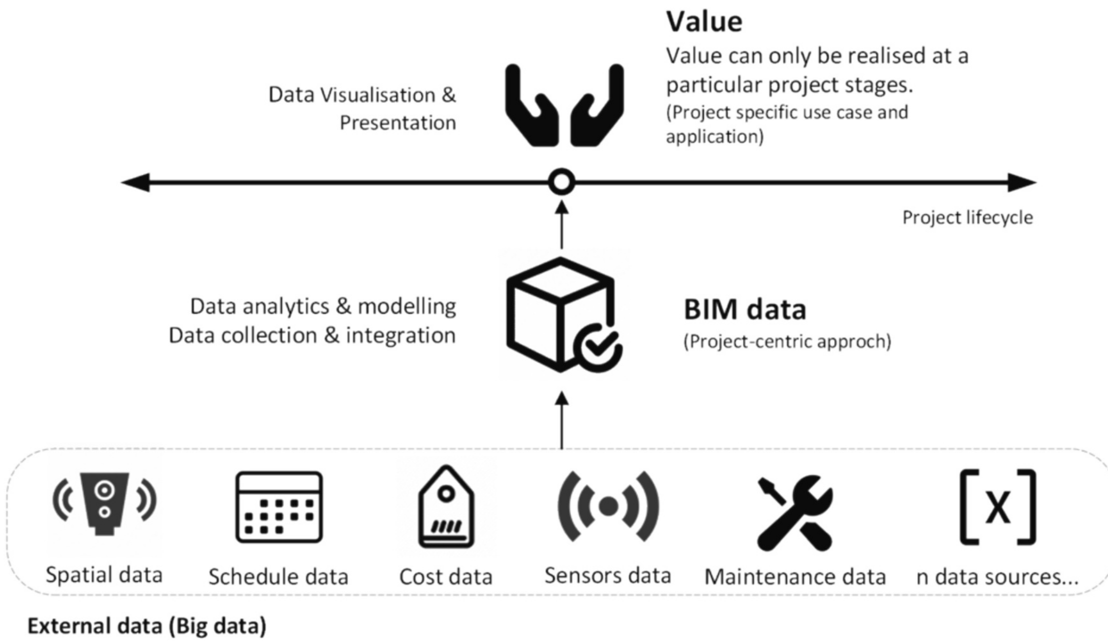

Fig. 8. Current AEC organisational infrastructure and processes research approach.

complexity and resource intensiveness associated with implementing BIM and big data technologies. Based on this finding, organisational priorities often prioritise budget and resources towards post-construction activities, resulting in less investment in early-stage data implementations.

Nonetheless, implementing BIM effectively during construction

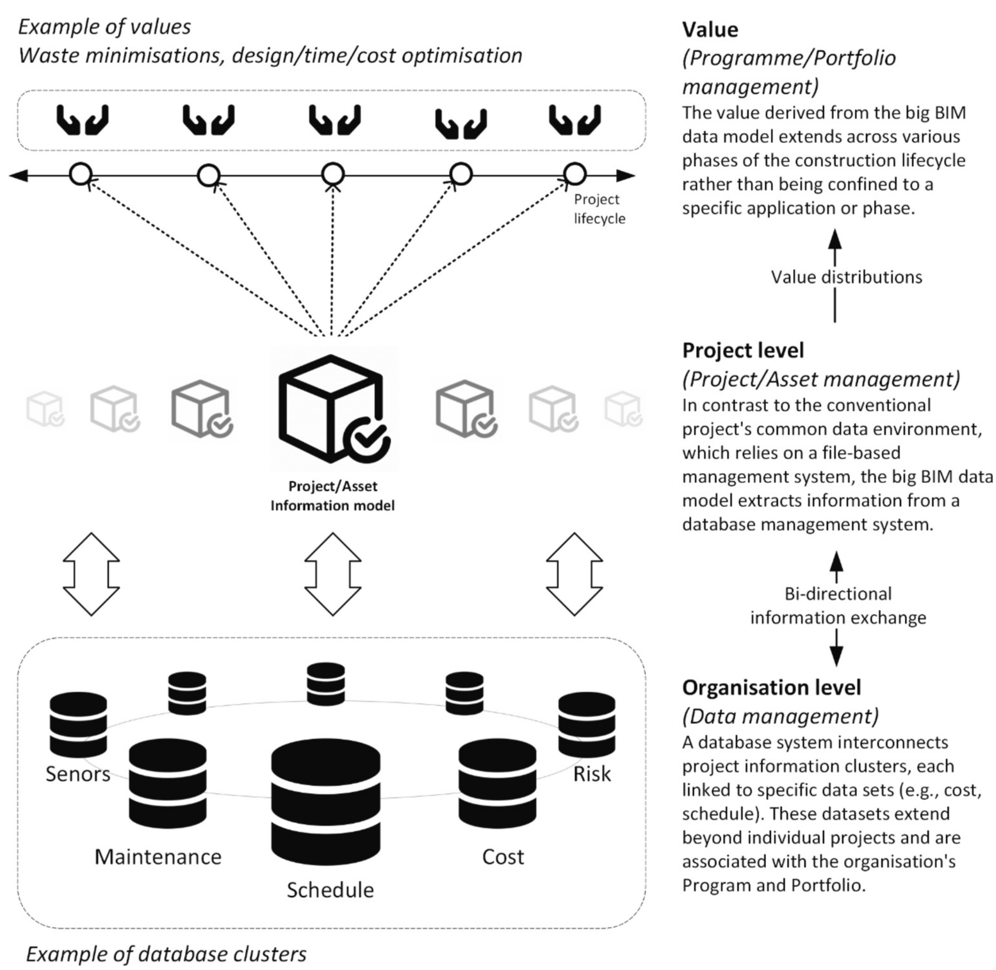

Fig. 9. Future research approach based on organisation centric data management.

demands real-time data collection, synchronisation, and interpretation. However, the uncertainty inherent in construction activities can lead to difficulties in maintaining the accuracy and coherence of big BIM data throughout the process. Additionally, construction projects involve various stakeholders and subcontractors who may lack prior experience or consistent familiarity with BIM or big data technologies. Integrating these technologies into ongoing construction operations requires comprehensive training, effective communication, and standardised protocols across diverse teams, presenting logistical challenges.

Post-construction stages encompass a substantial portion of an asset's lifecycle and offer significant potential for reaping benefits from various technologies. These technologies profoundly influence operational efficiency, maintenance protocols, historical preservation, and overall asset performance during this extended phase. Thus, leveraging big BIM data and associated technologies becomes more conducive and advantageous in these stable and controlled post-construction environments.

Future studies in this domain should delve into the administrative structures essential for the comprehensive adoption of big BIM data technology across organisations and different phases of the construction project lifecycle. These structures should facilitate data-driven organisational processes, starting with strategic planning for data collection, storage, and utilisation. During the construction phase, protocols for real-time data capture and communication are imperative. This involves implementing BIM-enabled collaboration platforms and integrating IoT devices for on-site data collection. Post-construction, robust systems for long-term data management and asset maintenance are crucial. Integrating BIM models with facility management systems and establishing protocols for ongoing data updates ensure sustained value from big BIM data beyond project completion, see Fig. 9.

Furthermore, addressing the need for new AEC skill sets is paramount. Training programs and educational initiatives should focus on developing skills in data analysis, project management, BIM modeling, and information management. Executive board members, senior staff, and operational personnel must acquire these skills to effectively leverage BIM technology and drive innovation throughout the construction project lifecycle activities.

6.1.2. Business – Big BIM data big BIM data (IT) infrastructure and processes gap

The research on IT infrastructure and processes complements organisational strategic goals by focusing on the technical requirements necessary for successful implementation and delivery of value from big BIM data, particularly system architectures. Unlike AEC organisational infrastructure research, which tends to focus on specific project phases, IT infrastructure research aims to provide a comprehensive platform for collecting, integrating, storing, analysing, and visualizing big BIM data throughout the project lifecycle. This includes technologies like databases, cloud computing, and blockchain, often integrated with secondary supporting technologies such as IoT and sensor networks. Future research in this domain should expand its technological scope to include a wider range of analytical algorithms and emphasise the systematic competencies of the platform. Additionally, there should be a focus on the processes of big BIM data technology within the organisational setting and its interactions with external stakeholders. The shift from file-based management systems to database management systems (DBMS) highlights the need for more sophisticated data governance policies and processes.

In the AEC sector, traditional file-based information exchange and Common Data Environments (CDEs) have led to data inconsistency and challenges in managing large volumes of BIM data Alreshidi et al. [5]; [23]. To address these challenges, there is a growing trend towards incorporating DBMS for managing and exchanging datasets and metadata [38,71,118,123]. This approach emphasises structured data architecture for semantic interoperability across the project lifecycle, ensuring efficient data management and exchange (Fig. 10).

Currently, data governance challenges in information management are being addressed through national frameworks such as Australia's Digital Engineering Standard, aligning with international standards such as ISO 19650 [54]. These standards govern information management using BIM technology and incorporate classification systems including but not limited to Uniclass 2015, OmniClass etc. However, transitioning towards a comprehensive big BIM data approach requires more than just classification systems. Advancing beyond traditional data management requires further research and exploration to fully harness the potential of big BIM data.

6.1.3. Business – Big BIM data: AEC organisational strategic framework research gap

Organisational strategic analysis and framework research are primarily aimed at providing strategic frameworks, conceptual models, and systematic reviews to guide AEC organisations. These studies offer insights into emerging technologies, AEC market trends, and the value proposition of integrating big data, BIM, or a combination of both within the organisation. While such studies may not directly deliver tangible benefits to organisational strategic value, they provide a holistic view of the organisational and industry landscape. They also assess organisational distinctive competencies and governance factors. Future research in this domain should expand its scope to include integration with AEC organisational infrastructure and processes research, as well as IT infrastructure and processes research. As highlighted in Henderson and Venkatraman [45], these domains cannot be developed in isolation.

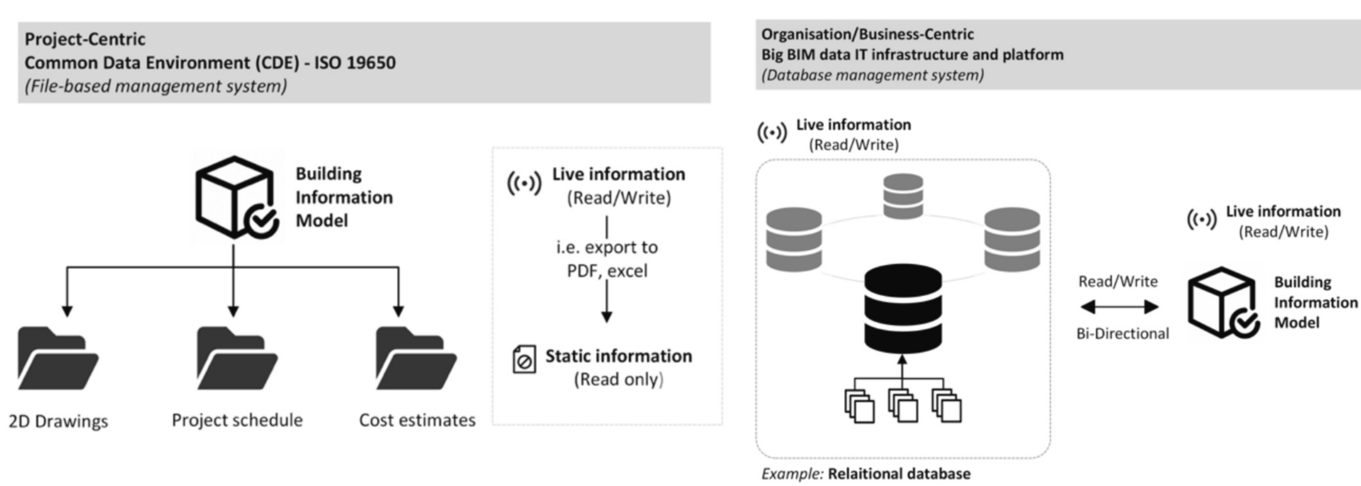

Fig. 10. Traditional File-based Common Data Environment (CDE) based on ISO 19650 vs Database management system.

Therefore, a comprehensive approach is needed to ensure alignment and synergy across organisational strategy, infrastructure, and processes.

The SAM proposed by Henderson and Venkatraman [45] presents a holistic view of the core drivers underpinning data management practices. At its core lies the interplay between data and information. Information, typically associated with business strategy, revolves around the practical utilisation of data. On the other hand, data is linked with information technology and the processes essential for managing systems that facilitate data accessibility [32]. This model comprises four fundamental domains of strategic choice, including business strategy, information technology strategy, organisational infrastructure and processes, and information technology infrastructure and processes. Aligning these domains requires careful consideration of how the value derived from managing big BIM data fits within the operational framework of the organisation, see Fig. 11. In essence, defining a strategy for big BIM data should be tightly interwoven with the identified organisational needs, aiming to articulate requirements that delineate measurable and tangible benefits in organisational terms.

6.1.4. BIM data (IT) strategic framework research gap

The strategic analysis and framework for Big BIM data aim to provide comprehensive guidelines for integrating big BIM data infrastructure and processes within AEC organisations. These studies primarily emphasise conceptual frameworks, and the development of a Big BIM data IT benchmarking system for evaluating information systems processes. However, future research should broaden its focus to include IT architecture and processes to address fundamental issues in BIM research, such as data loss, inconsistency, errors, and liability for incomplete or incorrect data [5].

Ineffective metadata management exacerbates these challenges, hindering data retrieval and reuse across projects and asset lifecycles. To tackle this issue, BIM-based organisations leveraging big data technologies should adopt a comprehensive metadata tagging approach. This involves tagging all project deliverables with relevant metadata fields spanning the asset lifecycle, discouraging disconnected or project-specific metadata fields in favour of universally applicable, interoperable semantics. Embracing a business-centric perspective is crucial, particularly in metadata attribute classification systems, ensuring uniform usage throughout the project lifecycle and promoting consistency and coherence in data management practices [32]. Additionally, the adoption of classification systems offers various benefits for organisational efficiency, including establishing uniformly structured data, standardising terminology, enabling intelligent search capabilities, facilitating data reuse for analytics, and creating machine-readable data in structured databases. Integrating such systems enhances data management practices, enabling streamlined operations and informed decision-making across the organisation's projects [2].

Another research gap lies in understanding the requisite skills necessary to operate IT organisational infrastructure effectively. Unlike research on AEC organisational infrastructure and processes, which focuses on acquiring new skill sets tailored for executive board members, senior personnel, and operational staff, the emphasis here is on skills required to directly support IT infrastructure and processes. These skill sets include roles such as Chief Data Officer (CDO) and Chief Information Officer (CIO) at the executive level, as well as Chief Data Steward and Data Management Executives among senior members. Operational staff within the organisation, such as Enterprise Data Architects, Data Modelers, and IT support personnel, also play a crucial role in ensuring the effective implementation and maintenance of IT infrastructure and processes [32].

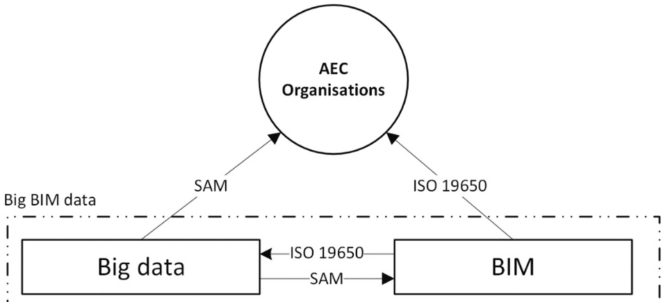

Fig. 11. Conceptual linkage between Big Data, BIM and AECO organisations under the SAM and ISO 19650.

6.2. The need for the AEC organisational- big BIM data strategic alignment framework

The SLR highlights several limitations in existing studies, which are predominantly conceptual, based on small-scale experiments, or represent early-stage research. These studies often lack a comprehensive understanding of broader organisational needs and overlook the strategic aspects of implementing big BIM data. Instead, they primarily focus on individual projects or assets within specific lifecycle phases, limiting their applicability to practical settings. While informative, these studies may not fully address the complexities of broader organisational strategies for adopting or replicating the benefits of big BIM data, particularly in the context of applications during project and asset lifecycles.

Building upon the literature findings and identifying research gaps, this study introduces a model designed to conceptualise and guide the emerging field of strategic big BIM data management. This model, named the AEC Organisational -Big BIM Data Strategic Alignment Framework, draws inspiration from the SAM. It comprises four essential domains of strategic choice: AEC business strategy, big BIM data (IT) strategy, AEC organisational infrastructure and processes, and big BIM data (IT) infrastructure and processes, each with its own underlying dimensions.

The study proposes that to effectively utilise and harmonise big BIM data within the AEC organisational context, future research should focus on two key aspects of strategic management: strategic fit and functional integration. Strategic fit involves aligning external and internal components, while functional integration focuses on integrating AEC business and functional domains. Leveraging the identified four essential domains of strategic choice, organisations can gain a comprehensive understanding of how to align their business and IT strategies, organisational processes and enhance integration between business functions and IT domains. A summary of the future research framework is illustrated in Fig. 12.

Furthermore, this study aims to explore stage 3 of the ISO 19650 digital maturity model, a phase that remains largely unexplored by many organisations. It proposes the utilisation of the SAM framework as a valuable tool for organisations seeking to develop a roadmap towards stage 3. This stage highlights the critical need to align business strategies with Big BIM data, as depicted in Fig. 13. Hence, SAM serves as a crucial link between the evolving definition and standardisation of ISO 19650 and the maturity levels of BIM implementation. During this phase, organisations are responsible for crafting a strategic framework to manage BIM processes and standards. This entails aligning organisational objectives, goals, and strategies with the effective utilisation of IT resources, encompassing not only big BIM data but also supporting technologies such as cloud computing, databases, IoT, etc.

Furthermore, recent updates to the model demonstrate the integration of object-based server big BIM data models with various components. This integration encompasses both strategic alignment and value assessment of integrated big BIM data. Additionally, it involves technical alignment, including the management of connected databases and metadata across business and technology layers, respectively.

Fig. 14 introduces a comprehensive framework designed to steer future research endeavours, spotlighting the four pivotal domains of

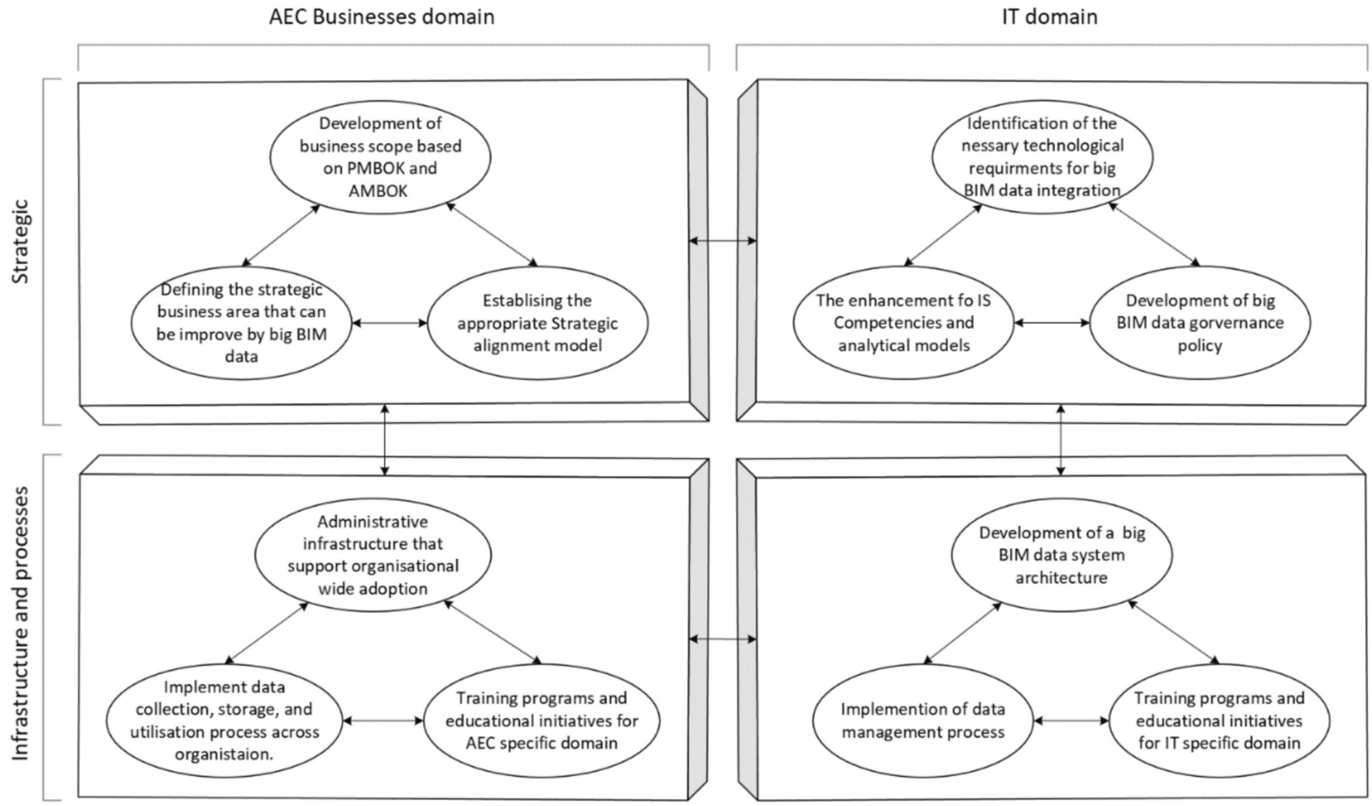

Fig. 12. Future research framework.

strategic choice outlined in Fig. 12 and advocating for their implementation across diverse hierarchical levels. This framework is crafted with the intent of establishing a harmonious structure across three key layers: project, organisation, and industry alignment. As depicted in Fig. 9, the intricate interconnection of databases underscores the imperative for uniform standards and alignment not only within individual organisations but also across the broader industry spectrum. Therefore, alignment initiatives must transcend the confines of organisational and project levels to ensure seamless integration and interoperability among various stakeholders within the industry.

At the level of individual projects, the framework would facilitate the seamless integration of big BIM data into project planning, execution, and management processes. This includes ensuring that project teams have access to the necessary data resources and tools to support informed decision-making and project outcomes. By incorporating big BIM data into project workflows, organisations can enhance collaboration, efficiency, and productivity throughout the project lifecycle.

Moving up to the organisational level, the framework promotes the alignment of big BIM data initiatives with overarching organisational strategies and goals. This involves establishing clear objectives for big BIM data utilisation, developing standardised processes for data collection, analysis, and dissemination, and fostering a culture of data-driven decision-making within the AEC organisation. By aligning big BIM data efforts with broader AEC organisation objectives, organisation can maximise the value derived from their data assets and drive innovation and growth across the enterprise.

Furthermore, the framework emphasises the importance of industry-wide alignment in advancing the adoption and utilisation of big BIM data. This includes fostering collaboration and knowledge-sharing among industry stakeholders, developing common standards and best practices for data management and interoperability, and advocating for policies and regulations that support the responsible use of big BIM data. By working together as an industry, stakeholders can overcome common challenges, accelerate innovation, and drive positive change in the built environment sector.

Nevertheless, it is essential to meticulously consider the alignment between the three layers—project, organisation, and industry. This consideration is vital for facilitating the effective implementation and harmonisation of strategies across the construction ecosystem, ultimately fostering enhanced collaboration and innovation within the industry.

7. Conclusion

The increasing reliance on data underscores the significant value embedded within data assets. Many organisations are adopting a 'data-driven' approach to stay competitive, prioritising data-triggered decisions supported by analytics over instinct-based judgments. This shift towards data-centricity highlights the need for efficient data management, which requires a combination of business leadership and technical expertise.

The main contribution of this paper lie in its comprehensive and systematic exploration of integrating big data within the BIM landscape for AEC organisations. This study offers a thorough overview of the current status, trends, and applications of big data in BIM so called "big BIM data". By employing the PRISMA framework, the study ensures a rigorous and transparent literature review process. Covering the period from 2013 to 2023, the study categorises 125 articles into four major domains: AEC organisational infrastructure and processes, big BIM data (IT) infrastructure and processes, AEC organisational strategic domain, and big BIM data (IT) strategic domain. These categories were validated using a quantitative method, bibliometric analysis, which includes keyword extraction and co-occurrence mapping, offering novel insights into the most frequently discussed topics and emerging trends in the field. The analysis of 10 keyword clusters identified through bibliometric analysis further enhances the understanding of these topics.

Through a qualitative analysis, the study identifies practical benefits of big BIM data in the AEC sector, particularly emphasising

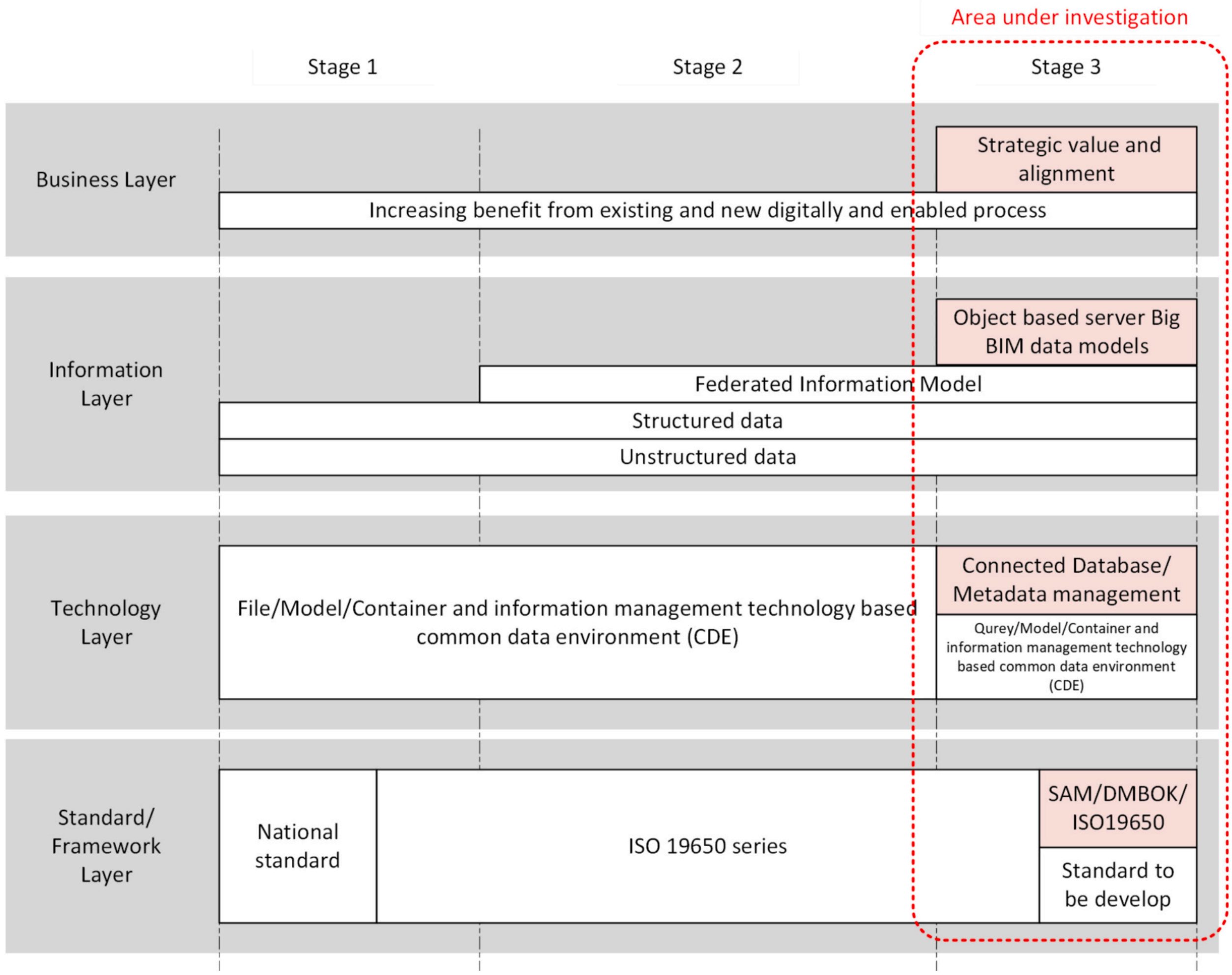

Fig. 13. Digital maturity model adopted from ISO19650-1 [54].

advancements in post-construction phases due to mature technologies like sensor networks and IoT devices. Challenges persist in obtaining usable data during pre-construction and construction stages, mainly due to onsite deployment constraints. In the domain of big BIM data (IT) infrastructure, technologies such as databases, cloud computing, and blockchain are pivotal for comprehensive data collection, integration, storage, analysis, and visualisation throughout project lifecycles. Organisational Strategic Analysis explores business scope, competencies, and governance factors relevant to big data and BIM adoption, while big BIM data (IT) Strategic Analysis focuses on strategic frameworks for infrastructure adoption, addressing technological scope, competencies, and governance. These domains provide conceptual models and reviews of current trends, progress, and future directions in big BIM data adoption within the AEC industry.

Furthermore, the study integrates diverse theoretical frameworks and standards such as DMBoK, PMBoK, AMBoK, ISO 19650, and SAM to develop a deeper understanding of the subject. This structured, multidimensional analysis not only enhances the current understanding but also outlines future research pathways in the AEC industry's use of big data and BIM, marking the true novelty and contribution of this work.

Based on these findings, four significant research gaps were identified, each corresponding to the domains established during the analysis. Addressing and resolving these research gaps will play a crucial role in the proposed framework, named the AEC Organisational - Big BIM Data Strategic Alignment Framework. This framework not only addresses organisational aspects but also emphasises the interconnectedness between individual projects, organisational levels, and industry-wide alignment.

Limitations of this study include its reliance on journals sourced from Scopus, Web of Science, IEEE Access, ScienceDirect, and Google Scholar databases. As there may also be other additional databases housing research on BIM and big data, the study's scope might have missed relevant papers. Despite analysing a substantial number of papers compared to other reviews, more extensive investigations are required to mitigate these limitations and enhance understanding in this field. Additionally, while the search terms used were considered appropriate, there might be other articles under different keywords, implying potential limitations in search term choices. Regularly updating these terms would enhance the theoretical and empirical development of this domain.

CRediT authorship contribution statement

Apeesada Sompolgrunk: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Saeed Banihashemi:** Writing – review & editing, Validation, Supervision, Project administration, Methodology. **Hamed Golzad:** Writing – review & editing, Validation, Supervision. **Khuong Le Nguyen:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

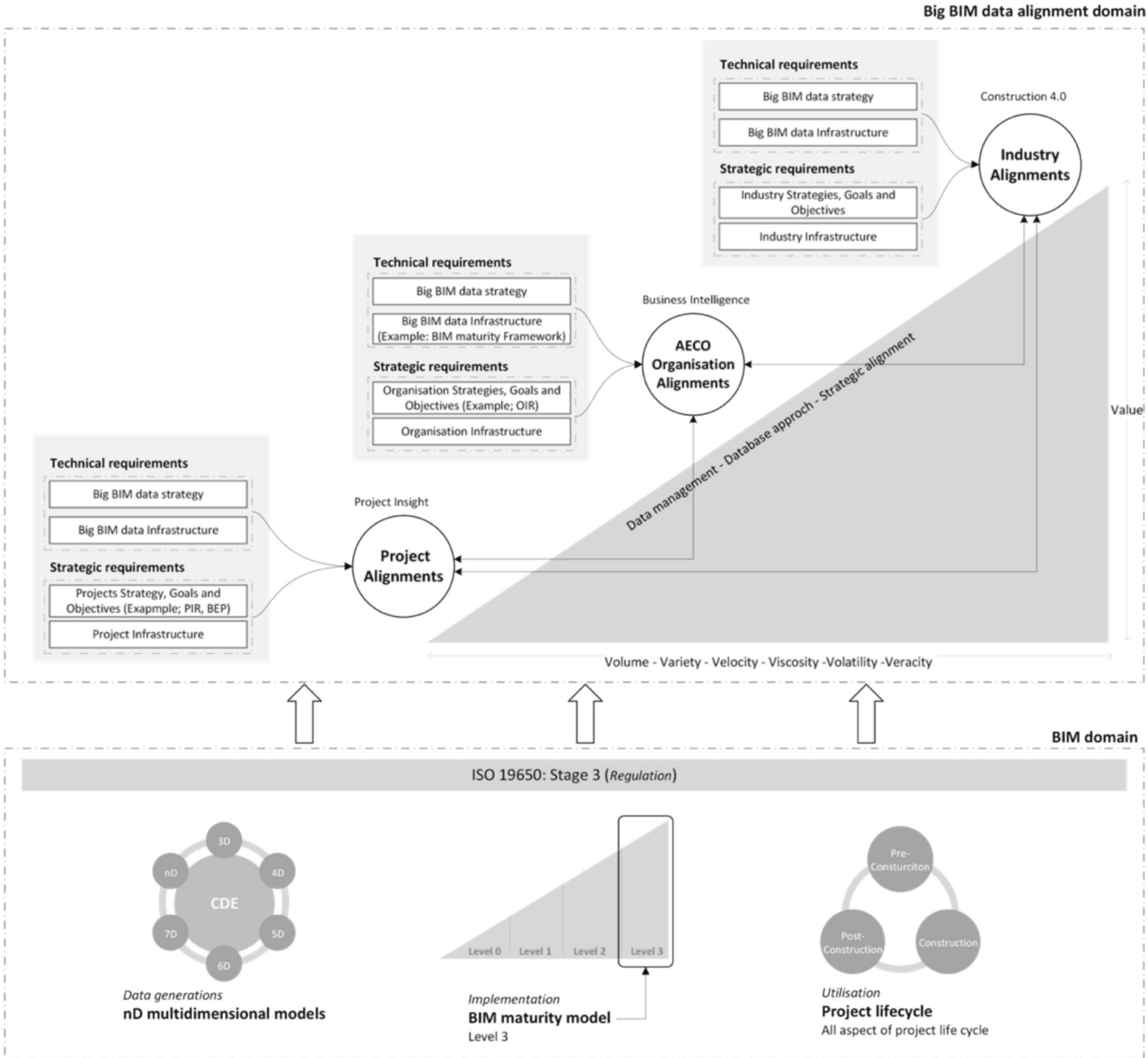

Fig. 14. AEC Organisational -Big BIM Data Strategic Alignment Framework.

the work reported in this paper.

Data availability

No data was used for the research described in the article.

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